Concrete with improved visibility in low light conditions

by

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Declaration

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Abstract

In a world where the sun sets at the end of every day, humans are forced to move about in low light conditions, for which they are not specifically adapted to do. This is even more prevalent in modern times where sunset does not mean resting time. When travelling in low light condition, objects which cannot be seen can serve as hazards. With concrete being one of the most popular building materials used for constructing infrastructure, and its inherent material properties which make it less visible in low light conditions, motivates this study to improve the visibility of concrete in low light conditions.

Additionally, some materials used to create structures create darkness by blocking natural light which makes travelling within these structures difficult especially in an emergency. This is another inherent property of a concrete matrix which can be improved.

This study incorporates and combines different existing concepts to produce a concrete design which would aid in making concrete more visible in low light conditions. These include transparency and luminescent concepts. These concepts can increase the visibility of the concrete as well as enable light to pass or move through the structure, illuminating any dark environments.

The study focusses on the use of luminescent materials, in specific luminescent aggregates and luminescent powders, to provide an inherent visibility in low light conditions. To produce translucency, material such as fibre optics, glass and transparent resins are used. Each of the materials considered for this study was also characterised to better understand the behaviour of the material in the conditions in which it would be implemented.

The results of this study indicate that by incorporating and combining these concepts in concrete can improve its visibility in low light conditions. In addition, these concepts also serve as a mechanism to alter the aesthetics and the efficiency to some extent of concrete as a building material.

The influence on the durability of concrete by the incorporation of these materials was also investigated. The results indicate that the incorporation of limited amounts of these materials have a low impact on the durability of concrete, however with an increase in quantities the impact becomes more significant.

Afrikaanse opsomming

In ‘n wêreld waar die son ondergaan aan die einde van elke dag, word die mensdom geforseer om te reis of rond te beweeg in lae lig kondisies, waarvoor die mensdom nie noodwendig aangepas is nie. Díe is selfs meer relevant in die moderne tye waar die sons ondergang nie rus-tyd beteken nie. Wanneer daar in lae lig kondisies rondbeweeg word, kan voorwerpe wat nie gesien word nie, dien as gevare. Beton is een van die mees populêre boumateriale wat gebruik word vir die bou van infrastruktuur, maar die inherente materiaal eienskappe maak dit minder sigbaar in lae lig kondisies. Dit maak dus, ‘n studie wat die sigbaarheid van beton in lae lig kondisies ondersoek en moontlik kan verbeter, relevant en nodig.

Verder blok sekere materiale, wat gebruik word om strukture op te rig, natuurlike lig. Dit veroorsaak donkerte binne in die struktuur en maak dit moeilik om rond te beweeg in die struktuur, veral tydens ‘n nood situasie. Hierdie is nóg ‘n inherente materiaal eienskap van ‘n beton matriks waarop verbeter kan word.

Hierdie studie inkorporeer en bring verskeie konsepte saam om ‘n beton ontwerp konsep voor te bring, wat sal help om beton meer sigbaar te maak in lae lig kondisies. Hierdie konsepte sluit beide deursigtigheids en liggewende konsepte in. Die inkorporasie van hierdie konsepte sal help met die sigbaarheid van beton, asook om lig in staat te stel om deur die struktuur te beweeg. Dit sal dan die gevormde donker omgewing verminder deur beligting te verskaf.

Die studie is gefokus om liggewende materiale, in spesifiek liggewende aggregaat en liggewende poeiers, te gebruik om inherente sigbaarheid in lae lig kondisies te lewer. Om deursigtigheid te bekom, is materiale soos optiese vesels, glas en deursigtige harse ingestel. Elke materiaal wat ondersoek is vir hierdie studie was gekenmerk om die gedrag daarvan in die kondisies waarin dit geïmplimenteer gaan word beter te verstaan.

Die resultate van die studie wys dat deur die inkorporasie en saambring van hierdie konsepte kan die sigbaarheid van beton in lae lig kondisies verbeter word. Verder, kan dit ook dien as ‘n meganisme om die voorkoms van die beton, sowel as die doeltreffendheid daarvan, te verander.

Dit was wel gevind dat met die instelling van hierdie konsepte in die beton, word die duursaamheid van die beton verlaag. Indien daar beperkte hoeveelhede van hierdie materiaal gebruik word, is dit steeds nie aanvaarbaar laag nie.

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List of abbreviations and symbols

T	Absolute ambient temperature
ASR	Alkali silica reactions
f_s	Aperture number
a.u	Arbitrary units
d	Average specimen thickness
K_c	Calibration constant for the camera
cd	Candela
k	Coefficient of scattering
A_s	Cross-sectional area of specimen
k	D'arcy coefficient (Section 3.3.6)
°C	Degrees Celsius
N_d	Digital number of pixels in the image
r	Distance from the light source
Dy^{3+}	Dysprosium ion
E	Energy of a photon
t	Exposure time
UVC	Far ultraviolet
FBG	Fibre Bragg Grating
v	Frequency
GaN	Gallium nitrate
g	Gram
g	Gravitational acceleration
Rs.	Indian Rupee
IR	Infrared
P_0	Initial pressure
I_0	Input intensity
S	ISO Sensitivity of the film
K	Kelvin
kg	Kilogram
kN	Kilonewton
LED	Light emitting diode

l	Litre
lm	Lumen
L_s	Luminance of the scene in candela per square meter
MPa	Megapascal
m	Meter
με	Micro strain
UVB	Middle ultraviolet
mm	Millimeters
ω	Molecular mass of oxygen
nm	Nanometer
UVA	Near ultraviolet
NEF	Nikon Electronic Format
OPC	Original Portland Cement
OPI	Oxygen permeability index
Pa	Pascals
h	Planck's constant
POF	Plastic optic fibre
PMMA	Polymethyl methacrylate
P_t	Pressure at time t
RCG	Recycled crushed glass
RPW	Recycled plastic waste
B_r	Restricted light flow
Sm^{3+}	Samarium ion
z	Slope of regression line
Ω	Solid angle in steradians
R	South African Rand
sr	Steradian
TIFF	Tagged Image File Format
Tb^{3+}	Terbium ion
A	The area of an imaginary sphere
t	Time
Alq_3	Tris (8-hydroxyquinoline) aluminium

UV	Ultraviolet
R	Universal gas
A_u	Unrestricted light flow
V	Volume of cylinder (Section 3.3.6)
W	Watt

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1 Introduction

Once the sun sets or the lights go out, the 'normal' way people experience the world changes. The way people navigate and move around changes as people perceive the world around them differently. Humans are better adapted to be active during day time and often find it hard to travel after dark without sufficient light. In certain parts of the world, people are forced to travel in darkness or limited light, be it for duty or pleasure. With less lighting available in some areas, comes an increase in the risk of traveling. Objects that are hazards when easily visible, become even more so after dark when they are less visible. With concrete being one of the most popular construction materials in the world (Naik and Moriconi, 2005), many objects are constructed using concrete, such as bridge pillars, roadway barriers etc. One of the inherent problems of concrete is the low visibility thereof in low light conditions, thus additional measures should be put in place to attempt to make these objects more visible, such as adding streetlights or reflective road signs.

Several inventions have been put into production and operation to attempt to remedy the problem of traveling or moving about in low light conditions to safely guide users away from hazards, such as the reflective 'cat eyes' on roads, and reflective road signs, battery powered emergency lights, solar powered streetlights etc. These are very effective and have aided in making traveling safer in low light conditions, but there is always room for improvement. Even if sufficient artificial light is provided to illuminate concrete structures, it can easily be taken away when the required power to operate the lights is lost. For example, experiencing power outages, battery backup failure, theft of infrastructure etc. If concrete as a building material can be made inherently more visible in low light conditions, the dependency on these measures would be reduced.

According to the Central Intelligence Agency World Factbook the total length of road in the world equates to 64.3 million kilometres (The Central Intelligence Agency's Office of Public Affairs (OPA), 2019). Additionally, it is stated that 40% of the total 1.35 million deaths per year on the roads (World Health Organization, 2018), occur during night driving (Butler-Adam, 2018). In South Africa there were a total (day and night time) of 12944 fatalities recorded on the roads, in 2015 (Butler-Adam, 2018). This is a good indication that additional efforts are required to attempt to improve driving conditions. As time and resources are limited, narrowing this down to lighting conditions and visibility of hazards on roads in the dark can help to improve one part of the problem.

Some researchers aimed at using luminescent materials to aid in this problem. A luminescent material, of which various different types exist, can be defined as a material that receives excitation energy from a source and then releases the energy in a visible light frequency (Edgar, 2017). According to Edgar (2017) the action of light being released by luminescent material is termed as: "to luminesce".

A material which receives energy from a light source in the form of photons is defined as a photoluminescent material, which would be the luminescent material focused on in this study.

Previous research by Kuennen (2015) at the University of Purdue used the application of a sealant on concrete to make the concrete luminescent, while research by Zhao et al. (2013) investigated the influence of luminescent materials on concrete properties. The research indications motivated the attempt to expand the field of application of these materials, initiating this study. Many could potentially benefit if the aforementioned concepts could be incorporated into concrete to reduce the dangers of travelling in low light conditions.

People do not only travel outside, but also within built structures. When concrete structures are built, the normal way to get light into the building is by using windows or sky-lights, seeing that the concrete material does not let any light travel through. This can be changed with the incorporation of light pathways through the concrete. However, as soon as openings are incorporated into concrete, the concrete loses its insulating properties, as air can now travel through the concrete. Additionally, the concrete matrix is weakened as air cavities reduce the mechanical properties of concrete. Using light conducting materials in the concrete, instead of having air voids, can reduce the negative impact on the mechanical properties and especially the insulating properties. When considering that most buildings require additional interior lighting even during day time, it can be seen as an ideal opportunity to improve the manner in which natural light is incorporated into building designs. The concept of translucent concrete has been established by researchers such as Kamdi (2013) and Pilipenko et al. (2018). It can be seen as beneficial to improve the visibility of concrete in low light conditions, which can be directly related to the reduction of artificial light necessary in dark interiors.

Concrete surfaces are often covered or painted to produce a more aesthetically pleasing structure. Only more recently has the aesthetical value of concrete in different forms been recognised (Toogood, 2014). As a result of this, many have started to use exposed concrete surfaces to save on cost and to contribute to the aesthetic value of structures (Toogood, 2014). Thus, any additional alteration to concrete appearance should be welcomed, to further enable users to efficiently make use of new and even better aesthetic values of concrete. Since aesthetics is mostly seen as a qualitative aspect not a lot of time has been invested into producing a quantitative measurement thereof. It can be said that if the concepts incorporated to improve the visibility of concrete, and effectively increasing safety, can also improve the aesthetics thereof, then designers would be more likely to incorporate the concepts.

1.1 Problem statement

Concrete is one of the most popular building materials (Naik and Moriconi, 2005); however, an inherent problem of concrete is that the visibility thereof in low light conditions is limited, thus making a concrete structure a potential hazardous object. Furthermore, a concrete matrix, in terms of light conditions on the inside of structures, blocks all light from passing through, creating a dark interior.

1.2 Objectives

The objective of this study is to develop a concrete concept which would improve the visibility of concrete, specifically in low light conditions, and to make a concrete unit such that it blocks less light from passing though the unit. The focus would be to create a concept that incorporates different existing concrete concepts to serve as an improvement or addition of currently available concrete concepts.

1.3 Report layout

The layout of this report has been divided into five sections.

Chapter 2 consists of the literature study done on the relevant topics in order to complete this research, this includes topics such as light emission, transparency, aesthetics and finally safety.

Chapter 3 consists of the experimental framework used during the completion of experiments to have quantitative results.

Chapter 4 discusses the results obtained from implementing the experimental framework outlined in Chapter 3.

Finally, Chapter 5 draws conclusions from the results obtained, taking into account the topics discussed in Chapter 2, additionally making recommendations on what is suggested for future research.

2 Literature study

This chapter discusses previous research that has been done regarding the concept of luminescent and translucent concrete. This includes concepts that are necessary to understand luminescent material, luminescent concrete and other aspects incorporated into the study.

2.1 Light emission

Light is a wave that passes through space in a similar way as microwaves and x-rays. The wave can be at different wavelengths, but the human eye can only perceive in the range of about 400 nm to 700 nm wavelengths. The different wavelengths are perceived as different colours, with shorter wavelengths being cooler colours such as blue and longer wavelengths being warmer colours such as red (OMEGA, 2018).

2.1.1 Electromagnetic spectrum

The majority of the research done in this study is based on light and the generation thereof by a source of light, thus it is important to revise the basics of light waves. Visible light is merely a wave that falls within the electromagnetic spectrum. Different wavelengths are used to differentiate between types of waves. These different waves are: radio waves, microwaves, infrared (IR) waves, visible light, ultraviolet (UV) waves, x-rays and finally gamma rays (Patel et al., 2019). In Figure 2-1, redrawn from (Patel et al., 2019), it can be seen at what wavelengths the different waves are found. The light humans can see falls within the visible light wavelength between 380 nm and 740 nm, which includes a small range of the ultraviolet light and also infrared light up to 790 nm. Within this range of wavelengths, the observed colour of the light changes. Shorter waves are perceived as cooler colours such as violet and the longer wavelengths are seen as warm colours such as red. Waves with a shorter length than visible light are classified as ultraviolet light, which falls between 10 nm and 400 nm (Patel et al., 2019).

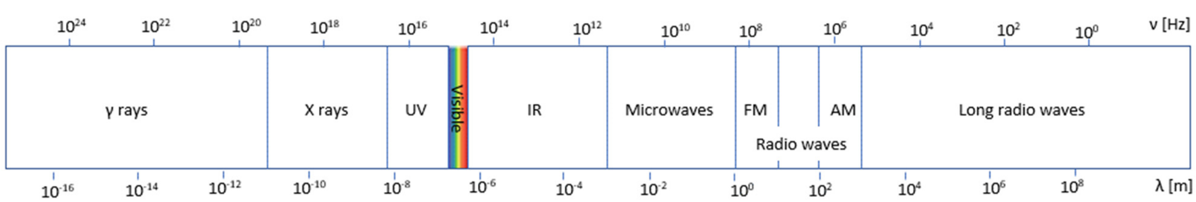

Figure 2-1 Electromagnetic waves (Source : Patel et al., 2019)

2.1.2 Ultra violet light

The term ultraviolet light is used for light in a certain wavelength group from 10 nm to 400 nm, within which there exists three classifications of UV light. The light is split in near ultraviolet (UVA), middle ultraviolet (UVB) and far ultraviolet (UVC) (Helmenstine, 2018). The UVC from the sun does not reach the earth surface as it is blocked by the atmosphere. Artificial sources such as fluorescent lighting, halogen lights and UV lights (bulbs) can also produce UV light. These vary in the amount of UV light emitted. Most of the UV light generated by the fluorescent light is blocked by the coating and the glass on the surface of the light (Helmenstine, 2018).

Halogen lights use pure quartz instead of glass, enabling it to emit UV light, except if a special high temperature resistant glass is used instead of the quartz or if the quartz is doped to prevent UV light from passing through. UV lights and black lights are specifically designed to emit UV light and can be dangerous if directed into the eye. An UVA light is less dangerous than UVB light, thus for most light sources the UVB light is blocked but acceptable amounts of UVA light are allowed to pass through. It is said that the fluorescent lights contribute to approximately 3% of the total UV light exposure to humans. Transparent glass prevents UVB light to pass through, but UVA can pass through, and tinted glass still lets 60 to 70% of UVA light through (Helmenstine, 2018).

2.1.3 Measuring light intensity

The collective group for visible light measurements is called luminous intensity. This photometric quantity is representative of the intensity of the light source as perceived by the human eye. The International System of Units (SI units) for luminous intensity is Candela (cd), which is defined as the intensity of a light source emitting an optical power of (1/683) watt at a frequency of 540×10^{12} Hertz into a solid angle of 1 steradian (sr) ("International System of Units," 2020). A standardised candle has an emission of 1 cd. Luminous flux is measured in lumen (lm) which can be defined the same as the candela except it is not limited to a solid angle (Schubert, 2018). In turn illuminance is measured in lux which can be defined as the luminous flux per unit area or lm/m^2 (Schubert, 2018).

Light energy is photons released from a source which then travels in a spherical shape away from the source. To measure the intensity of the source, the number of photons which hit a light sensitive sensor is detected by measuring the electrical charge being generated (as the photons carry energy). This electrical charge is then converted into a lux value for the user to interpret or to make use of. The energy of a photon is related to its frequency (ν) and Planck's constant (h) resulting in Equation 2-1 (Kennedy, 2020).

$$E = h\nu \qquad \textbf{Equation 2-1}$$

2.1.4 Sensitivity of the human eye

The human eye has a collection of light receptors which detect light and send signals to the brain, which then processes the frequency and intensity of the signal to determine the colour and intensity of the light source (Schubert, 2018). Red, green and blue receptors (cone shaped) determine the light frequencies and their range and the combination of the signals from the three colour receptors, this then enables the brain to decern what colour an object is. The eye also has rod-shaped receptors which cannot decern colour. For the human eye, three different vision regimes exist, being Scotopic-, Mesopic-, and Photopic vision. Each of these are used to describe the type of sensor combination used by the eye to detect light. The Scotopic regime is for luminance of lower (as low as 10^{-6} cd/m^2) than 0.003 cd/m^2, the Mesopic regime between 0.003 and 3 cd/m^2 and finally the Photopic regime for luminance levels higher than 3 cd/m^2 (Schubert, 2018). The daytime environment luminance would be classified in the Photopic regime (Schubert, 2018).

In the Scotopic regime, the human eye mostly loses its ability to decern colours as the main receptors used by the eye are the rod-shaped receptors. The Mesopic regime incorporates both the cone and rod shaped receptors in the eye, and therefore during day time (Photopic regime) the eye relies mostly on the cone shaped receptors to decern both colour and light intensity (Schubert, 2018). An article by Hadhazy (2015) on the human eye and the sensitivity thereof mentioned that each human eye has approximately 126 million light sensitive cells which can perceive light; however, each eye can differ resulting in a different perception to light. The eye perceives light by detecting photons that hit the cells in the eye. The brain then uses the signals received from the eye to determine shapes, colours and brightness of objects.

The cells in the eye only need a few photons to be able to detect light, and Hadhazy (2015) states that if as little as five photons hit five different cells, the eye can register it. When participants in a study, mentioned by Hadhazy (2015), were tested, it revealed that when 54 photons reached their eyes, of which some are filtered out by the lens, they could recognise a flash of light. When considering this, as long as the photons hit the cells, light can be recognised. Some studies state that a candle flame can be spotted from up to 48 kilometres, if no background light overwhelms the photons received by the eye from the source (Hadhazy, 2015). The same principle applies when looking at the stars, as they are very far away but the eye can still see them as a source and more stars can be perceived with less light pollution.

The human eye is more sensitive to green light wavelengths than others, meaning that an equivalent green, red and blue light source would not be perceived equally (OMEGA, 2018).

2.1.5 Luminescent material

Luminescent material is a term used to describe material that has been excited by an energy source, and then emits the energy in the form of light. Thus, from this statement, it can be derived that certain luminescent material can only be excited by certain energy sources, which then defines the type of luminescent material it is classified as. Table 2-1 shows the different types of luminescent materials available and their sources of excitation (Edgar, 2017).

Table 2-1 Different luminescent materials (Source: Edgar (2017))

Designation	**Excitation**	**Trigger**	**Acronym**
Photo luminescence	UV, visible photons	-	PL
Radio luminescence	X-rays, gamma rays, charged particles	-	RL
Cathodo luminescence	Energetic electrons	-	CL
Electro luminescence	Electric field	-	EL
Thermo luminescence	Photons, charged particles	Heat	TSL
Optically/ photo stimulated luminescence	Photons, charged particles	Visible or infrared photons	OSL, PSL

Photo luminescent material (which is the focus for this study) is defined as a material that is activated when exposed to a light source, in specific UV light and visible light, from which it absorbs photons, which carry energy. The material can store the energy for a limited time after which it will release that stored energy in the form of light. The light emission is not a pulse of light but rather in the form of a glow which is a steady release of the energy (Edgar, 2017).

As Figure 2-2 (Edgar, 2017) illustrates, there are three states in which luminescent material can be, being the ground state, which is the “uncharged” state, the excited state, being directly after exposure to an energy source, and finally the luminescing state. The material will always attempt to return to its ground state as that is the most stable state for the material (Edgar, 2017). Once the material is exposed to an energy source, the state would rapidly change from the ground state to the excited state. Once in the excited state, the material will start to emit the energy to reach the luminescing state, in this transition the material will appear to luminesce in a bright fashion as it is attempting to release a large amount of energy in a short time span. The transition between the luminescing state and the ground state is a longer one, as there is less energy available to be released. The final decay can occur as either radiative or non-radiative, and the release of photons is associated with the non-radiative decay (Edgar, 2017).

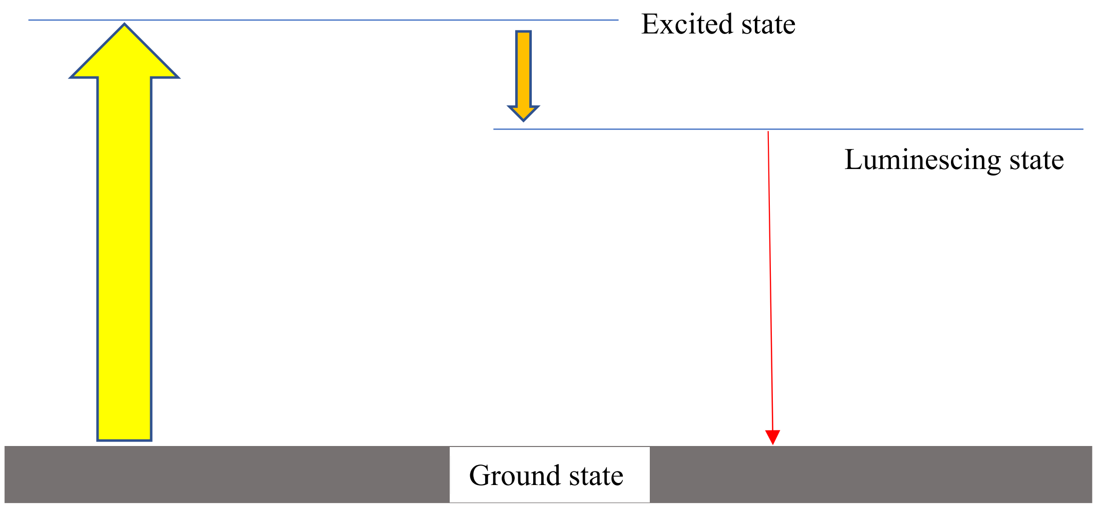

Figure 2-2 Luminescent material states (Source: Edgar (2017))

Two types of photoluminescent material classifications exist, being fluorescent and phosphorescent. The differentiation between a fluorescent material and a phosphorescent material is the time taken to transition from ground state to the other states and back to ground state, where under 10 nanoseconds will be fluorescence and longer would be phosphorescence. As a result of the time-domain response of the material, phosphorescence and fluorescence are known as luminescent material (Edgar, 2017).

For a long afterglow effect, a phosphorescent material is needed that can release the absorbed energy over a longer time span. Development of the long afterglow material has resulted in the material being able to release energy for up to 24 hours from the time it was exposed to a light source, depending on the chemical composition. This material can be expensive, but lower quality material would not yield sufficient light emissions (Edgar, 2017).

By using different raw materials to produce a different chemical composition with the phosphorescent as base, a different colour light emission can be achieved. This is useful as the different colour luminescent material can be used for different applications, such as colour coding different areas in a structure to indicate zone differences (Edgar, 2017).

Sources of photo luminesce

When looking at the inner workings of luminescent materials, luminescence in semiconductors and insulating material can be caused by different types of molecule centres. These centres include transition-metal ions, rare-earth ions, excitons, donor-acceptor pair and ions having a d^{10} or s^2 electron configuration (Edgar, 2017).

As discussed, there exists different types of photo luminescence. Naturally occurring minerals can vary in the amount of fluorescent intensity, with the same mineral not always having the same level of fluorescence. For a mineral to fluoresce, it requires an activator cation metal, such as tungsten, lead, boron, manganese, chromium, uranium, etc. (King, 2012). A crystal structure defect or impurities, such as yttrium, europium or samarium (Schneider, 2006), can also lead to a mineral fluorescing. The most common fluorescent material is fluorite, which was discovered in 1852 by G.G. Stokes, to have a blue glow. In the light of long afterglow materials, or phosphorescent materials, naturally occurring minerals which phosphoresce can be minerals such as calcite, colemanite, fluorite, celestite and phosphor (King, 2012). However, these are only examples of naturally occurring minerals, whereas some researchers attempt to create synthetic materials which too have the ability to photo luminesce. The following studies discussed also incorporate specific alterations to chemical compositions to be able to manipulate the colour of the phosphorescent material, of which in most cases the main photoluminescent compound is phosphor.

In the preparation of the luminescent material, rare earth ions contribute to an excellent luminescent material as they add to the chemical stability of the material, increase the luminous intensity and ensure a pure colour output. The most common rare earth ions used are that of europium and secondly that of dysprosium. Phosphor is currently the most used matrix for the luminous material but research shows calcium oxide, which was used for the specific study of Zhao et al. (2013), to be a good substitute for phosphor as a matrix.

A study was done by Yang et al. (2013) on a green luminescent material incorporating a doped phosphor to increase the performance and properties of the luminescent material. The basic phosphor material under consideration has a chemical formula of $Ba_3Bi(PO_4)_3$, which was then doped with terbium ions (Tb^{3+}). This was done as previous research by Blasse (1970) on the basic phosphor material indicated good luminescent properties and good clarity of colour. However, as that study focussed on only the basic material, Yang et al. (2013) decided to further investigate the luminescent properties of the material if it was to be doped with Tb^{3+}-ions. For the study, Yang et al. (2013) assumed that the Tb^{3+}-ions replaced some of the bismuth ions (Bi^{3+}) as both have the same valance and ionic radii. Thus, the resultant chemical formula for the material worked with was $Ba_3Bi_{0.9}(PO_4)_3$:$0.1Tb^{3+}$. When the material was excited with a 375 nm wavelength, an emission peak occurred at different wavelengths with the highest intensities being at 549 nm and 543 nm, of intensities 3900 arbitrary units (a.u) and 4200 a.u. respectively. This indicated that the doped phosphorous material is a good green emitting luminescent material, especially if used on light emitting diode (LED) and fluorescent lights.

As the most common luminescent material is green in colour, a study was done by Pekgözlü (2019) to produce a new reddish orange luminescent material. The basis for the study was to use a synthesised phosphor with the chemical formula of $Sr_3B_2O_6$ that was doped with samarium ions (Sm^{3+}). The expected emission spectrum for the ions was a transition between yellow, orange and red. For the experimental procedures, the chemical formula for the doped material was $Sr_3B_2O_6$:Sm^{3+}. The material was tested to establish at what wavelengths the material gets excited and the emission wavelengths thereafter. The results indicated several peaks between 200 nm and 500 nm wavelengths, with the largest peak being close to 400 nm. The emission spectra for the material excited by the 400 nm wavelength was measured and the two highest intensity peaks were at 600 nm and at 647 nm, with intensities of 2900 a.u. and 3300 a.u. respectively. When comparing the results to that of the pure $Sr_3B_2O_6$, the pure $Sr_3B_2O_6$ has no excitation at the 400 nm wavelength, thus doping the material with the samarium ions enhanced the luminescent properties so that it can be used as a reddish orange luminescent material (Pekgözlü, 2019).

Another study was done by Liu et al. (2014) to produce a white light emitting luminescent material. The dysprosium ion (Dy^{3+}) was considered for the study as previous investigations indicated that the ions produced a high intensity of blue and yellow emission, with a partial red emission. The Dy^{3+}-ions were used to dope $Ba_3Y(PO_4)_3$ (phosphor). The chemical formula for the research was $Ba_3Y_{1-x}(PO_4)_3$:xDy^{3+} with x being between and including 0.01 and 0.20, as the ions partially replace the Y-ions in the bond. Results indicated $Ba_3Y_{0.92}(PO_4)_3$:$0.08Dy^{3+}$ was the resulting composition. When considering the result for the excitation and emission, it was found that the material was excited at three distinct wavelengths being 340 nm, 360 nm and 380 nm, and the emissions peaking at 486 nm and at 575 nm. The results indicated that the material showed potential to be used as a near white light emitting luminescent material (Liu et al., 2014).

Porous gallium nitrate (GaN) is also considered as a luminescent material and many different techniques have been used to attempt to improve the luminescent emission of this material. Hou et al. (2018) investigated one of these methods being wet etching to roughen the surface of the GaN. For the study three different etchants were used; different variants of 1-ethyl-3-methylimidazolium based ionic liquid. The GaN was etched for different time periods to establish which would produce the best result. The GaN was etched for times of 1, 3, 5 and 7 minutes. The results indicated that at the same wavelength exposure, 365 nm, the 1 minute had the highest peak, decreasing with the increase in etching time. However, all the etching times resulted in a higher luminescent emission than the standard GaN. The 1-minute etching had a 9.27 times higher emission intensity than that of the standard GaN. This was as a result of the etching increasing the surface area by creating regularly arranged holes on the surface of the GaN, increasing the surface area available to emit light. This was a good indication that the etching of GaN does indeed increase the luminescence of the material (Hou et al., 2018).

From here onwards, photoluminescent material will be referred to as luminescent material.

2.2 Translucency

A transparent material can be defined as a material within which photons of light can adhere to Snell's Law by experiencing limited amounts of scattering or absorption by the material through which it is attempting to pass. If a material does indeed let some light through but some of the photons are scattered or absorbed, which means not all can follow Snell's Law, then the material is defined as translucent (Singh, 2014). If the material does not let any wavelength of light pass through, by absorbing the light or reflecting the light, then the material is considered as opaque (Singh, 2014). Figure 2-3 (Simmons et al., 2019) is a good illustration of the difference between the three concepts, with opaque being left, then translucent in the centre and transparent on the right. If the concepts can be described by everyday objects, a wooden door would be opaque, a textured bathroom window would be translucent and a kitchen window would be transparent.

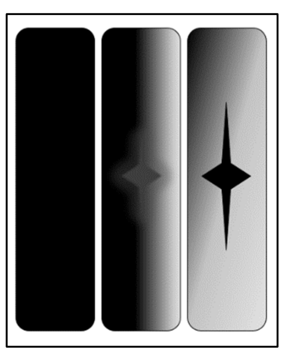

Figure 2-3 Opaque, Translucent, Transparent illustration (Source: Simmons et al., 2019)

2.2.1 Optical fibres

The optical fibre is defined as a thin fibre of plastic (plastic optic fibre (POF)) or glass through which light travels to transfer data (Hayes, 2019). The signals can be in either digital or analogue form. However, for this study the property of light conduction would be used for illumination purposes not data transfer purposes. Figure 2-4, drawn from (Hayes, 2019), illustrates a common optical fibre which consists of a core, cladding around the core and finally a buffer around the cladding (Hayes, 2019). The light, which travels in rays, is confined to travel in the core of the fibre. The cladding is used to add a confinement for the light to not escape the core, and the buffer is used to block out any interfering light rays from the surroundings, and protect the fibre against the environment (Hayes, 2019).

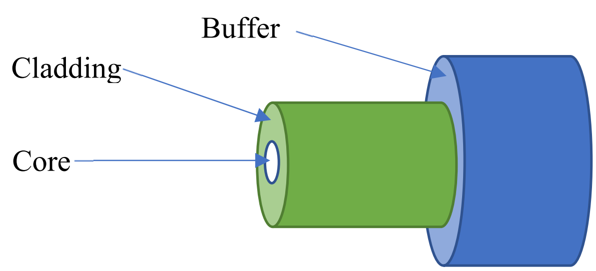

Figure 2-4 Optical fibre layering (Source: Hayes, 2019)

Figure 2-5 (Hayes, 2019), is an illustration of the core and the cladding around it, and in specific how a light ray will travel through the core of the fibre, at a level of detail which is relevant for this study. If the source of the light ray is perpendicular to the edge of the fibre, light would pass straight through a straight fibre (red line). If a ray from a light source enters the fibre at an angle, the light ray would be reflected off the inner walls of the cladding, to guide the light through the fibre core to the other open end of the fibre (Hayes, 2019).

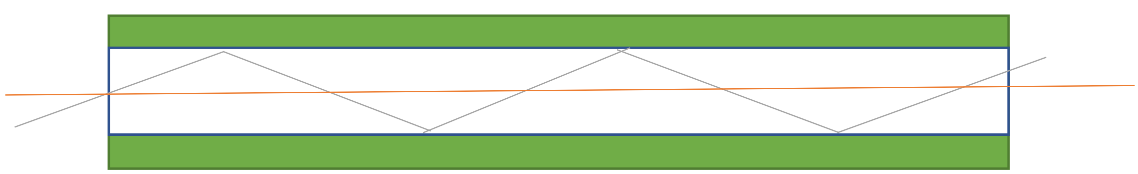

Figure 2-5 Optical fibre longitudinal section (Source: Hayes, 2019)

The entry angle of the light into a POF is limited to 60° from the centre line which is a greater angle than the 40° incident angle of the glass fibre (Zhou et al., 2009).

2.2.2 Side emitting fibres

Side emitting fibres are designed to leak light passing through the core of the fibre to the outside, through the side of the fibres. The side emission of the light can be designed to be continues or interrupted which each creates a different visual effect. These side glow effects can be achieved by means of incorporating different materials in the fibre such as air bubbles, fluorescent additives or changing the cladding of the side surface (Spigulis, 2005). Fibre optics have many different applications in the field of communication, décor, style, visual effects etc. As energy is lost during the side emission of light, Spigulis (2005) determined that Equation 2-2 can be used to describe the side emission over the length of the fibre.

$$I_s(x) = A \exp{(-kx)} \qquad \textbf{Equation 2-2}$$

With:

$$A = (4\pi)^{-1} \times I_0 \times (\exp k - 1) \qquad \textbf{Equation 2-3}$$

Where k is the coefficient of scattering and I_0 is the input intensity.

Using this model, it can be seen that when a single light source is connected to the one end of the fibre the glow intensity will decrease along the length of the fibre having one end with a lower brightness than the other. This effect can be counteracted by connecting a light source to both ends of the fibre. When using longer fibres, a light source with a higher energy output has to be used to ensure that the entire length of fibre can glow. Another option, to improve the uniformity of the glow throughout the fibre, is to have a light source at one end of the fibre and to attach a reflector at the other end of the fibre to reflect any remaining light still in the core of the fibre (Spigulis, 2005).

Different types of fibres are available, eg silica-core and plastic fibres. The difference is that the plastic fibre absorbs more light energy than the silica-core thus resulting in a darker glow. A quasi-uniform side glow of up to 30 m can be achieved (Spigulis, 2005).

A few advantages of the side emitting fibres are that they are safe to use in almost any environment as they do not produce any spark or generate any heat, are electrically safe, waterproof and chemically resistant to most chemicals (Spigulis, 2005).

A different type of glowing fibre is also available which is a polystyrene material coated with a fluorescent dye which is then covered by a clear acrylic coating to protect the dye. A fibre made up of material that becomes luminous after being exposed to daylight. This incorporates strontium oxide to allow a green-yellow glow of up to 12 hours (Spigulis, 2005).

2.2.3 Glass transparency

Glass is known for its transparent and brittle properties, thus the implementation of glass as a transparent material seems to be a logical choice. The reason behind the transparency of glass as a solid material can be attributed to the fact that glass is pure silicon dioxide which is known to not absorb light, and when the micro structure of the glass is created under controlled conditions, the scattering of light which hits the material can be controlled, enabling the solid material to be transparent (Tavel and Thomas, 1999). In the micro structure of glass, the distance between grain boundaries is small enough that the shortest wavelength of visible light is able to pass through the region between the grains.

According to a glass manufacturer (Croxsons, 2019), the colouration of glass containers is done such that the contents would be protected from harmful UV light and light which can cause oxidation of the product inside. When testing the application of crushed glass as a translucent aggregate, the effect of colouring in the glass has to be tested by comparing the difference between transparent and coloured glass aggregate. To have a consistent reading to compare the values of, the aggregate used has to be of similar size and shape to prevent diffraction of the light having an influence on the results. This is important to consider when choosing the glass as an aggregate, as the glass with the optimal light transmittance should be used to achieve the optimal output.

2.3 Luminescent concrete

A luminescent concrete can be defined as a concrete that incorporates a luminescent material or the combination of different luminescent materials into the concrete matrix to produce a concrete unit that can emit light after an energy source has been removed.

2.3.1 Glow in the dark sealant

Kuennen (2015) reported on a study done on the application of glow in the dark sealer on concrete pavement surfaces. The study entailed that the sealant was applied to the concrete surface and exposed to a light source, and then the duration for which light was emitted, was measured. It was found that the material was able to glow for up to 24 hours in a dark environment. The results of the tests indicated that the glow from larger strontium aluminate particles were longer present compared to the smaller particles. The sealant was argued to be able to increase the service life of the pavement in addition to supplementing the light of streetlights to improve public travel safety at night. For their study they exposed a sealant of soy methyl ester polystyrene mixed with strontium aluminate to a xenon light source which simulated the sunlight. Figure 2-6, by Kuennen (2015), shows the sealant on the concrete sample being exposed to a xenon light source from a close distance whereafter the luminescing sample is shown once the light is removed.

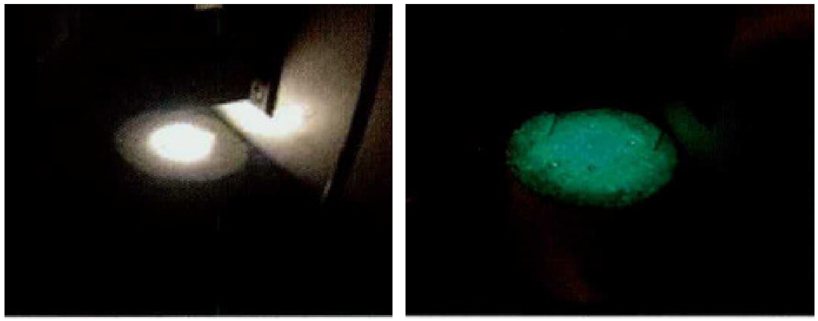

Figure 2-6 Testing of luminescent concrete sealant (Source: Kuennen, 2015)

Additional tests showed that the freeze thaw resistance increased and water penetration into the concrete reduced when the coating was applied (Kuennen, 2015). Considering the absorption of sodium chloride solution, the concrete with the applied sealant showed a 50% reduction in mass absorption, and for magnesium chloride solution a 25% reduction, and finally for calcium chloride solution a 20% reduction (Kuennen, 2015). The suggested use of the sealed pavement is to use it in light sensitive areas such as nature reserves, yet to have enough light to guide pedestrians improving safety at night, without disrupting any wildlife. Another proposed use for the sealant was also to replace some streetlights where applicable as the road user would still be guided but by using a more energy efficient light source. In addition, the sealant can be applied in construction zones to improve safety in low light conditions, showing exits in case of an emergency. However, the study did not make any reference to a test conducted on the skid resistance of the surface once the sealant was applied. A sealant being applied on the surface may introduce a lower coefficient of friction making it unsuitable for some applications.

Further tests on the material was done by Wiese et al. (2015) to determine the influence of different exposure times, using a Xenon arc lamp, on the brightness of the sealant over time. They stated that different exposure times had little to no impact on the brightness over time of the sealant.

2.3.2 Luminous concrete

The concept of the luminous concrete, as described by Zhao et al. (2013), is that during the day the concrete unit would absorb energy from sunlight and then release the energy after dark. The use of this material would be for aesthetic value and for illumination of environments and objects, such as for road markings and dividing lines on roads. The problem with long afterglow material is that it cannot be used on its own, it has to be mixed with other materials to achieve the desired effect. The material has to have a matrix in which it is placed to work in a desired environment (Zhao et al., 2013). Placing the material in concrete is the perfect solution for the built environment, as the concrete can be exposed to a light source while keeping the luminescent material in place, and not being damaged. Additionally, concrete is a popular building material, improving the availability of a suitable matrix.

The study on luminescent material by Zhao et al. (2013), in Section 2.1.5, mentioned that luminescent material (powder) was added to the concrete in mass percentages of cement of 2%, 4%, 6% and 8%. The influence that the luminescent powder had on the compressive and flexural strengths of the concrete, was tested. A reference mix achieved 35.22 MPa and continuing 32.71 MPa, 27.39 MPa, 25.81 MPa and 22.71 MPa were achieved for the compressive strength of the 2%, 4%, 6% and 8% additions respectively (Zhao et al., 2013). The flexural strength resulted in 5.50 MPa, 4.19 MPa, 3.87 MPa, 3.64 MPa and 3.46 MPa respectively (Zhao et al., 2013). The luminous concrete was cast into 10 mm, 20 mm and 40 mm thick slabs containing 2% and 8% luminous powder, which were cured for 7 days after which the slabs were exposed to 1 hour of sunlight and the luminous time was then measured. The results are tabulated and shown in Table 2-2. From the results it can be seen that as the thickness of the slabs increased, the luminescence time decreased and as the amount of Phosphor present increased, so did the luminescence time (Zhao et al., 2013).

Table 2-2 Luminescence time (hours) results (Source: Zhao et al., 2013)

Time unit (h)	**Thickness of slab (mm)**		
Phosphor dosage (%)	**10**	**20**	**40**
2%	5	4	2
8%	7	6.5	3.5

Gao et al. (2018) conducted research on the properties and mechanisms of luminescent cement-based pavement material, with the additional function of being super-hydrophobic. They investigated the influence of adding luminescent powder to concrete on the compressive and flexural strength of the concrete. The results for both the 3 day and 28 day tests showed that the strength of the concrete increases as the amount of luminescent powder increases. The increase in compressive and flexural strength can be seen up to 35% luminescent powder content, after which it starts to decrease again. The maximum flexural strength at 28 days was 7.5 MPa, at 35% luminescent powder content, and the compressive strength 56 MPa, also at 35%. The results obtained by (Gao et al., 2018) differ from the results obtained by (Zhao et al., 2013). This may be attributed to the combination of different raw materials, and the quantities thereof, used in combination with different mix designs.

For the luminescent properties of the concrete, it was found that the material light emission decays sharply over the first minute after the light source was removed. After the first minute, the brightness was down to about 27% of the initial brightness, however it maintained this brightness, of 0.02 – 0.16 cd/m^2, for up to 8 hours (Gao et al., 2018). The luminescent glow slowly decreased over the 8 hours. The study also revealed that as the amount of exposure time to a light source was increased, the brightness over the decay time was higher compared to that of the shorter exposure times. This also indicated that the material was luminescent for a longer time the longer the exposure to the source (Gao et al., 2018).

2.3.3 Nanoparticles with luminescence

Salah et al. (2013) did a study on an organic semiconductor molecule, namely tris (8-hydroxyquinoline) aluminium (Alq_3). This is a commonly used host for fluorescent and phosphorescent dyes. This was considered as it has been reported to have a good electroluminescence. For the study, they produced Alq_3 nanoparticles doped with silver, copper and terbium. The nanoparticles were produced on a substrate of glass and using a scanning electron microscope and an atomic force microscope it was observed that the particles were 70 nm to 80 nm spheres. Using the UV-visible absorption spectra it was determined that the maximum absorption was at a wavelength of 300 nm.

When the Alq_3 was doped with terbium, copper and silver it was found that the wavelength emitted was at a constant 515 nm with an increased intensity of the luminescence (Salah et al., 2013). The ratios of Alq_3 to silver were ranged between 1:0, 1:0.2, 1:0.4, 1:0.6, 1:0.8 and 1:1, and the influence of the changes was observed. The results indicated that the peak emission was at about the same wavelength, however as the ratio increased so did the intensity of the luminescence up to the 1:0.8 ratio, after which it reduced again. It was found that when the silver was used to dope the Alq_3 at 1:0.8 ratio, the luminescence was twice as bright compared to only Alq_3. The nanoparticles were considered as a new luminescence material as it can present new optical properties previously not available in other materials (Salah et al., 2013).

Steyn (2008) conducted a study on incorporating luminescent material as nanoparticles in the transport environment. The study included various application methods of the nanoparticles such as adding the material to bitumen, in both red and white road paint. Additionally, concrete mortar samples were prepared at 1%, 5% and 10% of nano phosphors added by the weight of cement in the concrete. The decay of luminescence was measured after the samples were exposed to two minutes of an artificial light source. To measure the decay of luminescence over time, a light dependent resistor was used. When analysing the results of the test, it was clear that as the amount of phosphor content increased the decay slope decreased, indicating a slower decay rate (Steyn, 2008). When comparing a green and a blue luminescent material, it was observed that the blue had a lower decay rate, especially at higher amounts. When considering the bitumen test results, an interesting result was observed. After the bitumen was exposed to durability tests (called a Hamburg Test), the sample had a lower decay rate than before being exposed to the durability test. This can possibly be attributed to the fact that more phosphor material was exposed with the bitumen layer covering the material being worn away (Steyn, 2008).

2.4 Translucent concrete

A translucent concrete can be defined as a concrete that incorporates a translucent or transparent material or the combination of different light conducting materials into the concrete matrix to produce a concrete unit that can transmit light from one surface through the concrete unit to the other surface. Thus, the impact of the inherent opaque property of concrete can be reduced.

2.4.1 Fibre-optic concrete

Fibre-optic concrete is defined as the concept where light can pass through the concrete from one side to the other by means of light conducting material. Kamdi (2013) proposed the use of translucent concrete as a green construction material for building, seeing that the concrete can allow light into the building, thus during the day less artificial light is needed to illuminate the building, thus saving energy. The execution of producing the translucent concrete was to embed 4 to 5% of the volume of concrete with the optical fibres. The suggested applications for translucent concrete are for the use as floors, pavements and load-bearing walls, also facades, interior and dividing walls. Kamdi (2013) stated that the optical fibres can conduct light up to 20 m, thus thick wall units are possible without the loss of light conductivity. An additional application, for the light transmitting concrete or so called LiTraCon, is to provide light to underground structures such as underground train stations. This can save large amounts on costs for providing sufficient light. By adding a controlled light source, the LiTraCon can be used to illuminate speed bumps in the dark and to guide people to exits during

Figure 2-7 Illustration of implemented LiTraCon (Source: Kamdi 2013)

emergencies in buildings, and create a unique lighting condition for structures at night. An example provided by Kamdi (2013) of the implementation of LiTraCon can be seen in Figure 2-7.

Sawant et al. (2014) did a study on translucent concrete using optical fibres, adding and comparing 0, 1, 2, 3, 4 and 5% addition at 3, 7 and 28 day strengths. The result was a steady decrease in compressive strength as the amount of fibres increased, reaching a plateau for 4 and 5%. In addition to the strength tests, light conduction tests were also conducted. Concrete blocks were exposed to natural light over a 12-hour period. Table 2-3 was compiled from the results discussed by Sawant et al. (2014) which indicates the intensity of light passing through the concrete units as the day went by. The results indicated that for a 4% addition of optical fibres resulted in the most efficient light conduction through the concrete unit, compared to other added quantities.

Table 2-3 Light conduction percentages (Source: Sawant et al., 2014)

Fibre percentage	Maximum percentage of light conducted through unit
0%	0%
1%	12.6%
2%	18.4%
3%	20.7%
4%	21.0%
5%	23.3%

A calculation was made by Sawant et al. (2014) on the efficiency of the concrete by calculating the saving by using the translucent concrete instead of using a 60-Watt light bulb. This was done under the assumption that a 60-Watt light bulb would be required to constantly be on for 8 hours a day to illuminate a room. The currency was however converted from Indian Rupee used by Sawant et al. (2014) to South African currency, the Rand, at a value of Rs.1 to R0.23.

For a 30 day of 8 hours per day at R1.11 for residential and R1.82 for public:

$$Power\ consumption = 60 \times 30 \times 8 = 14400 = 14.4\ units$$

Initial cost of 20 cubes of translucent concrete:

$$cost = R889.41 - R65.51 = R823.91$$

Cost of 1 year for a bulb in residential areas:

$$cost = 14.4 \times 1.11 \times 12 = R191.81$$

Time to pay off concrete units:

$$time = \frac{823.91}{191.81} \approx 4.3\ years$$

Cost of 1 year for a bulb in public areas:

$$cost = 14.4 \times 1.82 \times 12 = R314.50$$

Time to pay off concrete units:

$$time = \frac{823.91}{314.50} \approx 2.7\ years$$

The results indicate that the concept to use translucent concrete instead of the stated artificial light in a residential home may be deemed economical over a longer period, even more so for the public sector. After 4.3 years residential application would start to save money on illumination costs, and after only 2.7 years the public sector would save on illumination costs.

2.4.2 Resin incorporated concrete

Pilipenko et al. (2018) studied the use of LiTraCon for mass production and found that it is an expensive construction medium as the optical fibres are expensive, and so is the labour cost as it is not easy to construct LiTraCon units. Thus, Pilipenko et al. (2018) decided to conduct research on finding a possible alternative to optical fibres in an attempt to make the translucent concrete more accessible. The material under consideration was a translucent polymer resin. The resin, in the form of epoxy or acrylic resin, is already used on construction sites for example as glue. The use of a concrete layer setup was investigated, which would be produced only with fine aggregate and the resin. This would then form continuous layers in the concrete element (Pilipenko et al., 2018).

It was noted that if this method of application was to be used, the cost of the concrete units would not decrease, thus it was suggested that the concrete mix be adjusted to use lower costing material such as recycled crushed concrete aggregate. However, this then shows that using the proposed resin instead of the fibre optics does not decrease the construction cost, but can possibly show that the cost per amount of light is reduced for the concrete (Pilipenko et al., 2018).

When the polymer resin was introduced into the concrete mix, a good contact zone was created between the concrete and the hardened resin when considering the good bond strength characteristics. It was noted that as the resin was introduced at the hardened stage of the concrete, the resin improves the freeze thaw resistance of the concrete as the resin fills the open pores on the surface of the concrete. Nonetheless, a different method of application of the resin was to cast the concrete in layers, with separators between the concrete layers. After one day of curing the separators were removed and the resin was cast in place. The compressive strength showed an overall increase of 19-23%, which showed that good adhesion between the concrete and resin layers was present as no delamination was present (Pilipenko et al., 2018). With the resin layers being transparent, the concrete can transmit light from one side to the other, making it a possible replacement for the optical fibres in LiTraCon (Pilipenko et al., 2018).

A different approach was followed by Mainini et al. (2012) where the idea is to use a transparent resin which is cast into slots in the concrete which then allows light to pass through the concrete. They conducted experiments on semi-transparent concrete panels to determine the amount of light passing through the concrete having the light source at different angles. The resin, polimetilmetacrilate, used for the study was said to be 92% transparent and to have a good resistance towards UV radiation. The concrete panel used was of size: 1000 mm × 500 mm × 40 mm, which can be seen in Figure 2-8, also showing the light passing through the concrete.

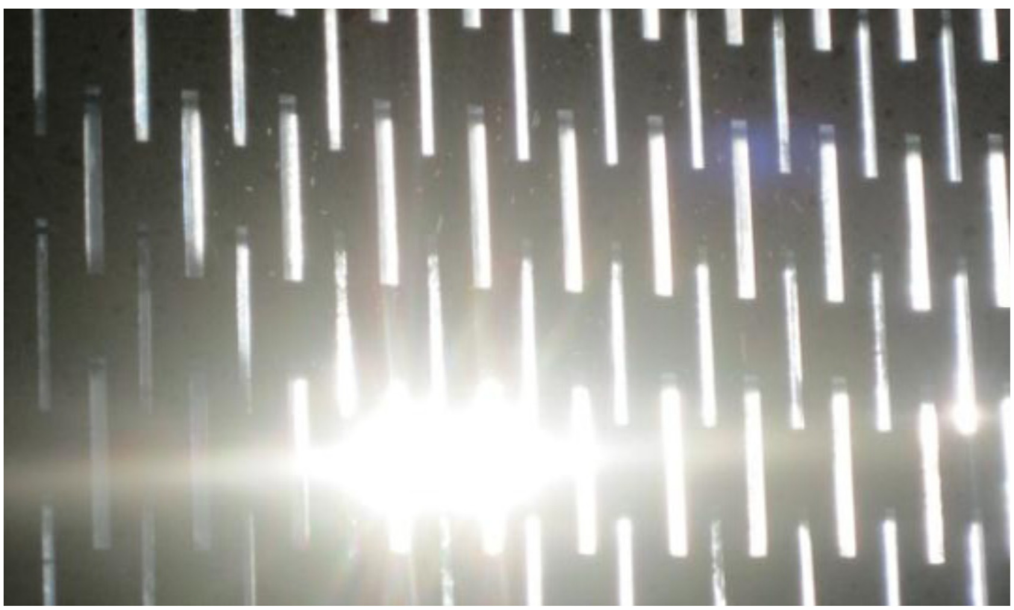

Figure 2-8 Semi-transparent concrete panel tested (Source: Mainini et al. 2012)

The results indicated that as the angle of the light sources increased, the amount of light transmitted reduced. The tests were conducted on two samples, one being in a horizontal position and one in a vertical position, both having similar results. The decrease in light transmittance as the incident angle increased can be attributed to the internal reflective properties of the resin, and the ability to reflect light from the contact interface between the concrete and the resin. As the angle increased, so did the dependency on the interface reflection (Mainini et al., 2012).

2.4.3 Compressive strength of translucent concrete

Luhar and Khandelwal (2015) conducted a study on how the addition of optical fibres to the concrete influences the compressive strength. For the testing procedures, three 70 mm × 70 mm × 70 mm cubes were cast with the optical fibres in place. The optical fibres were coated with a releasing agent on the ends that were in contact with the mould to prevent the fibres sticking to the mould, which could cause cracks in the concrete, during plastic shrinkage of the concrete in the fresh stage. The results for the tests indicated that compared to a standard concrete cube, the compressive strength decreased when the optical fibres were added, which could possibly be attributed to the lower compressive strength of the optical fibres as the load was applied perpendicular to the fibre length direction.

Two control concrete results were recorded as 38.77 MPa and 40.23 MPa, whereas the translucent concrete resulted in a 36.70 MPa compressive strength (Luhar and Khandelwal, 2015). The optical fibres were spaced at 8 mm apart from one another, by placing the fibres though holes in the mould wall, with the fibres making up 1% of the concrete cube volume. As the fibres were arranged by placing the fibres in the moulds before casting the concrete, a prediction could be made on where cracks would form during strength tests. The placing of the fibres in this format can influence the strength of the concrete cube when compared to a cube with fibres arranged at random. However, arranging the fibres in this ordered manner is necessary for the efficiency of the translucent concrete; it had to be ensured that both of the fibre ends are exposed to the concrete surface. The plastic optic fibre used in the study is described as a hollow cylindrical fibre (Luhar and Khandelwal, 2015).

A similar study on the mechanical properties of translucent concrete was conducted by Henriques et al. (2018), reporting a slight increase in compressive strength with a 2% volume of fibres in the mix and a reduction in compressive strength for greater fibre volumes.

2.4.4 Smart translucent concrete

A study was done by Zhou et al. (2009) and Lau (2014) on utilising the different properties of both plastic optical fibre (POF) and Fibre Bragg Grating (FBG) in concrete to create a concrete that can conduct light as well as to have continuous sensory capabilities. When the POF was compared to other light transmitting fibres such as silicon oxide (SiO_2) fibres, the POF can absorb light from a greater incident angle as the core of the fibre is larger, thus up to a 60 degree incident angle can be absorbed and transmitted. Additional advantages include a higher ductility and flexibility. The fibre optic strands transmit light in the form of electromagnetic waves which can be used to determine the conditions surrounding the fibres as the properties of the waves are influenced by several parameters. The temperature, stress, strain, pressure, magnetic field and electric field are external conditions that can influence the amplitude, polarized state, frequency and amplitude of the wave. If the changes in the waves are monitored it can give an indication of changes that occur surrounding the fibres (Zhou et al., 2009).

The fibres were cast into a resin (coloured), 4% of the surface area was taken up by the POF. A light source with wavelengths of both the visible and infrared was used to determine if the POF possesses light and thermal conduction capabilities. The result was a ratio ranging from 0.529% and 0.535% between the visible light and the infrared rays, indicating that it indeed has light and thermal conducting capabilities (Zhou et al., 2009). To test the detection capabilities of the fibres, they were cast into mortar cubes, having 3.14%, 3.80%, 4.52% and 5.3% area ratio of POF to mortar.

The results indicated that as the ratio increases so does the light transmitting ratio, as expected as more light paths were available. When testing the compressive influence of the POF on the concrete, a slight reduction in compressive strength was seen as the POF content was increased. The results were 201.8 kN, 201 kN, 195.7 kN and 182.2 kN for a 0.0%, 3.14%, 3.80% and 4.52% ratio respectively (Zhou et al., 2009). The FBG was used to compare the strain readings to that of a strain gauge, and the results showed that up to a strain of 2050 με the FBG produces about the same results as that of the strain gauge. The results from this test can be seen in Figure 2-9, where the FBG results are compared to that of a strain gauge, showing a very similar curve. This indicated that by using the FBG in concrete, an imbedded sensor is available for the entire life span of the concrete structure (Zhou et al., 2009). A detailed study on how FBG is used as a sensor system was reported by Lau (2014), that discussed how strain is determined from the various influencing factors.

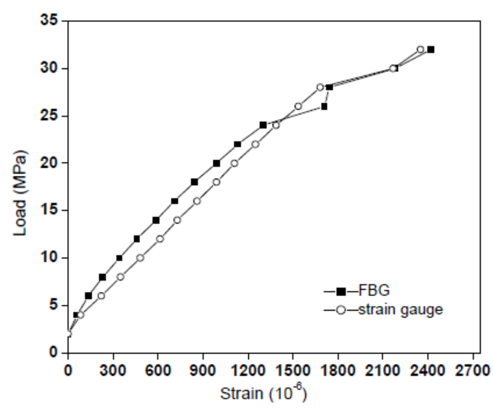

Figure 2-9 Test results comparing FBG to strain gauge (Source: Zhou et al., 2009)

2.4.5 Glass as aggregate for translucent concrete

The idea is to replace the coarse aggregate with recycled glass. The glass enables the light to pass through the concrete much like a window does in a wall, however on a much smaller scale. When using coarse glass aggregate, this effect will however only be achieved if the glass particles are in direct contact with each other. Depending on the available sizes of glass waste, the concrete units are usually limited to a thin member. This is however not ideal as the concrete units will then have limited applications. The limit on the thickness of the concrete member is due to the fact that the glass aggregate has to go from the one surface of the concrete to the other to enable light to pass through.

There is however an underlying problem when it comes to using glass material in concrete, which is that alkali-silica reactions (ASR) can take place. According to research done on ASR in concrete, finer milled glass particles have less ASR expansion than coarser glass particles as they partake in pozzolanic reactions in the concrete (Dhir et al., 2009).

Rashid et al. (2018) did a study on the use of glass waste in concrete and the effect thereof on the mechanical and environmental performance. The study found that as the amount of glass increased the workability decreased linearly, as well as the compaction factor of the concrete. The decrease in the workability was attributed to the shape of the glass particles, the flakiness of the glass and the poor adhesion of the glass particles to the constituents of the concrete. When the amount of glass content was increased, the bulk density decreased linearly. This is attributed to the difference in particle density of the glass material and conventional aggregate. For the compressive strength of the concrete, it was found that for 7 and 28 day strength, the compressive strength decreased, however for the 63 day strength test, the 20% glass material increased the strength above that of the 10% glass replacement, yet still lower strength than the reference concrete mix (Rashid et al., 2018).

Glasscrete is a term used to describe the use of post-consumer glass in concrete. The glass recycling process can however become a difficult process when the collected glass is contaminated by paper and metals. According to Jin et al. (2000) the problem with doing this is that alkali-silica reactions (ASR) could possibly occur between the glass and the concrete which aligns with Dhir et al. (2009). The ASR is as a result of the silica rich glass and the alkaline environment of the concrete. Jin et al. (2000) studied the theory behind ASR suppression which is relevant to the use of waste material in concrete. The study was aimed at the potential reactivity of aggregates and the long-term effects of the ASR. The ASTM C 1260 standard was used to complete the tests.

Seeing that ASR is a reaction that occurs on the surface of the glass particles, Jin et al. (2000) conducted a test to establish the expansion of mortar bars made up of 10% sand replacement with different glass sizes. The results indicated that the expansion was greater for the larger particle sizes

(300 µm, 600 µm, 1.18 mm, 2.36 mm) than for the smaller sizes, only the 150 µm and smaller particles had a reduced expansion compared to the reference mix (Jin et al., 2000) which confirms the results by Rashid et al. (2018). The relative expansion increased with an increase in the glass content as well as the increase in curing time. Different types of glass were used to replace sand in the mortar mix to compare the influence of the type of glass. The result indicated an increase in relative expansion for both Pyrex glass and fused silica as the particle size decreased until the 75 µm and 38 µm, respectively, were reached where a sharp decrease was noted. In contrast, clear soda-lime glass had a fairly constant relative expansion and decreased for the 600 µm sieve and then again at the 38 µm sieve (Jin et al., 2000).

Rouvas (2013) conducted a study on the utilization of glass in concrete for the purpose of translucent concrete. The aim of the study was to find a combination of good mechanical properties, ASR resistance and light translucency. Different mixes were tested which entailed the incorporation of different amounts of glass and different materials to establish the influence on the mentioned properties. The conclusion of the investigation was that partial or total replacement of natural aggregates with glass is possible, however reductions of 12.5% and 25% in tensile and compressive strength respectively occurred. The ASR was successfully suppressed by adding pozzolans to the mix even with the high glass content presents.

Rouvas (2013) determined if glass can be used in concrete to produce a translucent concrete. The test included different proportions of glass size grading aggregates. The results of the study indicated that as the thickness (between 4 and 13 mm) of the units decreased, the translucency of the unit increased in a natural logarithmic manner. Furthermore, the result indicated that the thickness of the concrete unit, which is translucent, is limited by the dimensions of the glass aggregate used, as the glass aggregate needs to reach both surfaces to produce translucency. For a concrete mix containing a total of 56.2% glass by volume of concrete, a 4 mm thick unit resulted in an average translucency of 2.2%, reducing to about 0.8% for double the unit thickness. The results obtained by Rouvas (2013) indicated that the use of waste glass material in concrete can indeed result in a concrete unit which is translucent to some extent.

The use of recycled plastic waste and recycled crushed glass in concrete was also investigated by Mohammadinia et al. (2019). The drive behind this investigation was the vast amounts of waste plastics and glass ending up on landfills, and the need to find an application for the waste to be utilized. The study focused on incorporating the recycled plastic waste (RPW) and recycled crushed glass (RCG) in concrete used for footpaths. The RCG was sourced from glass containers such as glass bottles or similar. It was noted that the smooth, unabsorbing surface of the glass posed a problem for bond-strength between the glass and cement paste. The RPW was between 4 and 5 mm, and the RCG was between 3 and 8 mm in size. Using cast cylinders, the resulting compressive strengths are tabulated in Table 2-4 (Mohammadinia et al., 2019). The RPW and the RCG were also mixed to achieve the same total content amounts, of which half of the total content of replacement was RPW and the other half was RCG. The compressive strength results can be seen in Table 2-4.

Table 2-4 Cylinder compressive strengths (Source: Mohammadinia et al., (2019))

	Compressive strength (MPa)		
Content (%)	RPW	RCG	RPW (0.5) & RCG (0.5)
10	38	56	44
20	26	45	32
30	21	40	29
40	13	34	23
50	6	31	20

For the tensile strength results, similar trends were followed when evaluating the concrete after 28 days, decreasing tensile strength as the amount of waste RPW and RCG increased. The amount of water uptake was tested by conducting a capillary uptake test. The results indicated that for most of the mixes the water uptake was similar or lower than that of a standard concrete mix. The explanation for this was that the RPW and RCG are unabsorbing (Mohammadinia et al., 2019).

2.4.6 No fines Concrete

The concept of having no fine aggregate in the concrete is to allow for air pathways through the concrete. These air pathways allow water to pass through the concrete, which has a popular application in the transport industry as water can now pass into the concrete and not pond on the surface causing risks to road users. This is especially used in areas with low traffic volumes such as parking areas, or sidewalks or driveways. This was developed to change the conventional approach towards storm-water management (Ghafoori and Shivaji, 1995). Another advantage of this type of concrete, is the lower normal-weight compared to conventional concrete.

According to Ghafoori and Shivaji (1995) the mix design for a no fines concrete is a mix with a single coarse aggregate size with a very low water to cement ratio resulting in an almost negligible slump. For the study Ghafoori and Shivaji (1995) compared concrete mixes with different aggregate to cement ratios being 4:1, 4.5:1, 5:1 and 6:1. After mixing the concrete, a visual inspection was done to ensure all the coarse aggregate is evenly coated with cement paste. The results show that the density of the concrete reduced with the increase in the aggregate to cement ratio as the cement has a higher specific gravity than the aggregate (Ghafoori and Shivaji, 1995). The reduction from 6:1 to 5:1, 5:1 to 4.5:1 and 4.5:1 to 4:1 was 1.5%, 2% and 4.3% respectively. Table 2-5 which was presented by Ghafoori and Shivaji (1995) was converted to SI units and gives a good indication of the results obtained in their study.

For the purpose of this study, the values of interest would be the reduction in density and the porosity of the concrete. A lower density concrete with high porosity would enable more light to penetrate the outer surface of the concrete.

Table 2-5 Test results for study (Source: Ghafoori and Shivaji, 1995)

Aggregate -cement ratio	**Properties**	**CONSOLIDATION TECHNIQUE**			
		Hand-roddin g	**Impact Compaction [Pa]**		
			13.21	33.1	66.1
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*
4:1	Compressive strength (MPa)	15.6	11.3	15.5	19.4
	Split-tensile strength (MPa)	1.7	1.5	1.8	2.2
	Flexural strength (MPa)	3.0	2.2	3.0	3.2
	Density (kg/m^3)	1715.7	1642.9	1709.8	1800.3
	Air content (%)	23.1	27.8	23.4	19.9
	Porosity (%)	20.2	27.2	20.8	18.6
4.5:1	Compressive strength (MPa)	13.5	10.3	13.5	16.3
	Split-tensile strength (MPa)	1.7	1.4	1.6	1.8
	Flexural strength (MPa)	2.6	2.1	2.6	3.1
	Density (kg/m^3)	1676.8	1623.8	1651.7	1733.8
	Air content (%)	26.9	28.4	26.1	22.7
	Porosity (%)	26.1	27.9	25.8	21.6
5:1	Compressive strength (MPa)	12.4	9.0	12.3	14.8
	Split-tensile strength (MPa)	1.6	1.3	1.6	1.7
	Flexural strength (MPa)	2.5	2.0	2.6	2.9
	Density (kg/m^3)	1664.3	1600.4	1651.8	1676.5
	Air content (%)	26.3	29.3	26.5	25.4
	Porosity (%)	25.6	28.2	25.5	23.5
6:1	Compressive strength (MPa)	11.3	8.6	11.1	14.0
	Split-tensile strength (MPa)	1.6	1.2	1.6	1.6
	Flexural strength (MPa)	2.1	1.7	2.1	2.6
	Density (kg/m^3)	1643.2	1581.2	1640.4	1665.6
	Air content (%)	27.5	29.6	27.7	26.0
	Porosity (%)	26.9	28.6	27.1	25.7

2.5 Aesthetics

As there does not exist a quantifiable measurement of aesthetics, but it is rather measured in a qualitative manner of the perception of an object, it is important to note what the common aspects are which would influence the aesthetics of an object, in specific a concrete object. According to Toogood (2014) it is the geometric shape of the concrete object, together with types of aggregates, surface finishing, textures and the colour of the concrete. When considering these, it can be deduced that the aesthetics of concrete can easily be altered. Small alterations in the design of the concrete and the construction using it can easily improve or decrease the aesthetics of concrete as a building material.

Furthermore, concrete which is often hidden behind paint and other surface appearance materials, is now being left exposed as more designers and architects realise the inherent aesthetic value of concrete, while saving on costs and production emissions (Toogood, 2014).

2.6 Safety

2.6.1 Evacuation times of buildings

According to different studies and mathematical models discussed by Galbreath (1969) the evacuation of a building depends on various aspects such as the amount of people on each level, the amounts of exits, the width of the stairways, the time taken to notice a fire, etc. When a mathematical model is used to calculate the evacuation time, the shortest time taken to evacuate an 11-storey building was 348 seconds (5.8 minutes). This was done for a building with a stair area of 13.94 m^2 and an average of 100 occupants on each floor. For this specific building a fire evacuation drill was conducted and the resulting time was 450 seconds (7.5 minutes). Evacuation drills were conducted for 7 to 18 storeys and all the times were under 10 minutes, not necessarily increasing as the storey count increased (Galbreath, 1969).

A further study on the evacuation times of tall buildings was conducted by Pauls (1987) and it was stated that the flow of occupants is a function of speed travelled times the density of occupants times the width of the path travelled. Additionally, it was stated that the evacuation time is then the sum of flow time and the travel time, of which travel time is a function of population and flow capacity. If occupants cannot seem to find their way to escape routes, the evacuation times would then considerably increase, thus it is important that occupants can easily find their way to escape routes, and furthermore be able to see how to navigate on the escape route.

When considering the application on the grounds of safety for the luminescent concrete, built structures such as any residential building, or office building or even sport facilities where evacuation of people is of the utmost importance in the event of an emergency. In the case of some emergencies, lights go out and individuals have to navigate out of the building in darkness. This can be mitigated by having luminescing concrete flooring. As the evacuation of a building should be done in as short a time as possible, the application of luminescent concrete is ideal. Any individual still in a dark environment after this time would have stabilised vision which has adapted to low light conditions, further enabling them to see the luminescing material. The luminescent concrete will therefore aid the safety signs in guiding people efficiently out of a building. This would also be applicable for cases where the electricity goes out and people have to navigate in darkness, especially when it comes to stairs, as stairs are harder to navigate in darkness. Additionally, as soon as the material is exposed to any light source containing UV light, it will be energised; ready to provide light as soon as the other light sources fail. To save on installation costs, the luminescent material can be focused along the edges of hallways or walkways and around exit ways, and only on the edges of stairs.

2.6.2 Road safety

In the light of road safety, one can argue that reflective signs are adequate in warning users of potential hazards, however, road signs can only be seen once light falls on the reflective surface. Implementing a light emitting material into either the road surface or onto the road signs can improve the effectiveness (visibility) of the warning.

A study was conducted in Saudi Arabia, by Saleem and Elshami (2017), towards the development of a lane separator, a cross section being displayed in Figure 2-10, using translucent concrete. The idea behind the study was to be able to transmit light through the lane separator to warn road users of obstacles in the road. This was an attempt to reduce the amount of accidents on the roads and the number of lives lost on public roads. The concrete units produced were imbedded with plastic optical fibres which would serve as a light path through the concrete. A light source would be placed under the concrete units which would be activated and controlled by a central computer. The operating computer will receive signals from sensors placed throughout the road surface which will detect if objects are stationary in the road warning road users by transmitting a red light through the lane separator.

For a certain distance from the obstacle all units will be red, after which a section would be yellow and then green. This was specifically designed for heaps of sand or snow etc. which are in the roadway endangering road users. The sensors work by detecting a constant pressure applied over a certain time frame which is an indication of a stationary object in the road (Saleem and Elshami, 2017).

Furthermore, for the study the compressive strength of the units embedded with the optical fibres was tested and compared to a reference mix. The results showed that at 28 day curing time the compressive

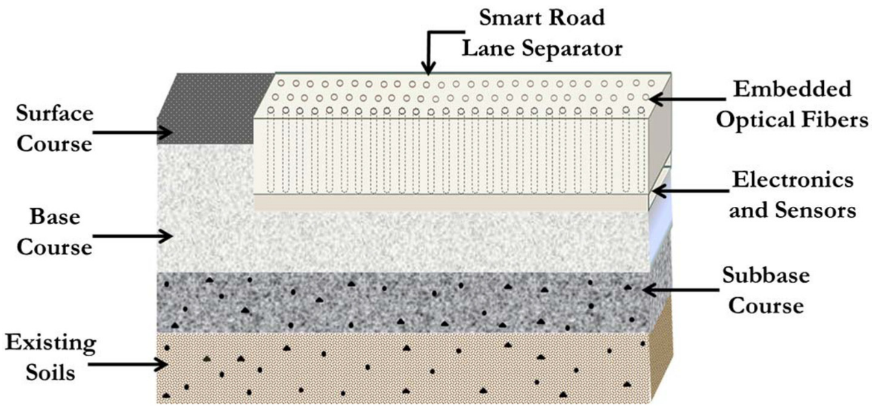

Figure 2-10 Layered cross-section of the suggested lane separator (Source: Saleem and Elshami, 2017)

strength decreased by an average value of 4.1 MPa, from 36.71 MPa to 32.6 MPa, when the optical fibres were imbedded in the concrete (Saleem and Elshami, 2017). This reduction in strength was attributed to less bond strength between the concrete and the plastic tendons in the concrete paste. As these units will be installed in the road surface it is of high importance that the specified skid resistance is achieved. Saleem and Elshami (2017) concluded that the skid resistance of the units was lower than the specified requirements, thus the surface finish should be adjusted when casting the units.

2.7 Concluding summary

In this section many previous studies were discussed on different concepts which are applicable to have sufficient knowledge to complete the research required. Considering previous research, it can be said that a reputable amount of knowledge is available on each of the topics discussed, however no previous research could be found which incorporates all the topics into one collective concrete group. Thus, there is an opportunity to add information into the world of research of building materials, the built environment and the transport environment. By conducting this study, more information would be made available on the implementation of the individual concepts in concrete, and in specific how effective the combination of the different concepts is in improving the problem of the low visibility of concrete in low light conditions.

3 Experimental framework

Various experiments were required to complete the experimental work required for this thesis. These include both laboratory work and field work to test the various components. The results discussed in Chapter 4 were obtained using the methods discussed in this chapter. In this chapter the materials, different measurement methods, the test setup to implement the methods and finally the test program used are all discussed.

3.1 Materials

3.1.1 Luminescent materials

For this study, the use of a luminescent aggregate was implemented. The aggregate was sourced from Chryso SA, and is commercially called LuminTech. Figure 3-1 (left) shows the aggregate under normal daylight conditions, and (right) the aggregate luminescing during low light conditions after being exposed to excitation energy. The suppliers stated that the aggregate is made such that it has similar physical properties as other coarse aggregates used in concrete. The aggregate is produced using a polymer-based product which is then crushed into the aggregate seen in the figure (Chryso, 2020). Further details of the product were deemed as sensitive information by the company.

The aggregate was characterised to better understand the behaviour thereof under different light conditions.

Figure 3-1 Luminescent aggregate (Left - in normal light, Right - luminescing aggregate) (Source: Chryso, 2020)

A luminescent powder (Phosphor H_2N) was also used in this study. Figure 3-2 shows the powder produced by Glowbug. This is the same luminescent powder used in the production of luminescent paint (glow in the dark paint) (Hollis, 2018). The luminescent powder was considered along with the aggregate to investigate the different types of luminescence that can be achieved from each, having different compositions and textures.

Figure 3-2 Luminescent powder in container

3.1.2 Transparent materials

For this study, different transparent materials were tested to determine the efficiency of light conduction through each medium. This was done to understand how the material behaves in conjunction with a certain light source and to be able to create light pathways into the concrete for the applications of having transparent concrete, and additionally have light energy be conducted to luminescent material imbedded in the concrete.

Three different materials were used for their transparency properties; resin material, plastic optical fibre, and lastly glass.

Resin material

Two different resins were used, in order to compare efficiency. The first is described as a standard casting resin (232PA) and the second is a (Polylite 32032-20) ultra-clear casting resin, both sourced from AlliedFibreglass. The standard casting resin makes use of a 2-stage mix, which is ratioed 2:1 of resin and hardener, and the clear cast makes use of a droplet hardening agent. Both resins are specifically produced to be transparent in nature, making it ideal for this study.

Plastic optical fibre

A plastic optical fibre or POF, in specific a (Polymethyl methacrylate) (PMMA) POF, was used for this study. Its properties of flexibility and relatively low cost, compared to glass fibres, are ideal. When considering the fibre optic material as light conduction material, similar to the resin tests, the material should be tested to establish its light conducting capabilities. For this study only the light conduction property of the POF was utilised, and not the data transferring capabilities. Fibres with a diameter of 0.7 mm and 2 mm were considered. Each of the fibre cross-sections comprises of a light conducting core and a cladding surrounding the core as discussed in Section 2.2.1. In Figure 3-3 a side elevation of both fibre diameters can be seen.

Figure 3-3 Different diameter POF strands

Glass

The glass used for this study to serve as transparent material is glass sourced from recycling. The glass was washed, crushed and classified as 12 mm aggregate size. The glass sourced was limited to clear glass. In Figure 3-4 the glass aggregate used is illustrated, and it can be seen that the majority of the aggregates are smaller than 12 mm, however the largest in the batch was 12 mm in its smallest measurement.

Figure 3-4 Glass aggregate

3.1.3 Concrete materials

For the purpose of this study, the materials used to create a concrete and/or a mortar mix were kept similar for continuity and for the purpose of sourcing materials. The mix proportions used for each experimental method were given with the relevant method.

The cement binder used was an OPC CEM II 52.5 N cement from the same bag (as small volumes were needed), with a relative density of 3.14.

The sand used is described as Philippi sand (dune sand) with a fineness modulus of 1.4 and a relative density of 2.62.

The stone used differed in size, either 6 mm or 13.2 mm, depending on the requirements of each experimental method, but was of the same type of stone which is locally known as Greywacke.

3.2 Test setup

3.2.1 Dark box

A dark box, seen in Figure 3-5, was built to conduct all the light sensitive experiments in, with dimensions of 1.5 m × 1.0 m × 0.82 m. The one side of the box was purposefully left uncovered to have an access point into the box to set up the light sensitive test. This end was covered with an opaque plastic tarp which was large enough that a person can stand under the tarp and still cover the side of the box in such a way that no direct light was able to enter the box.

Figure 3-5 Dark test box for light sensitive tests

The box was fitted with different light sources seen in Figure 3-6, such as an ultraviolet (UV) lamp, a fluorescent light and an infrared (IR) lamp which would be used to provide the excitation energy to the photo luminescent material. The different light sources were implemented to determine what wavelength would excite the material most, and what the brightness influence is on the material when exposed to light sources outside the common excitation spectrum. The light sources were selected such that a variation in the amount of UV light emitted was possible, as it was indicated that the UV spectrum effectively excites the material under consideration. Using a UV sensor, the UV light registered a power of 0.69 microwatt per square meter ($\mu W/m^2$), where-as the other two light sources in the dark box did not register on the meter (of 0.01 $\mu W/m^2$ sensitivity). For this reason, exposure to sunlight and a streetlight were also considered.

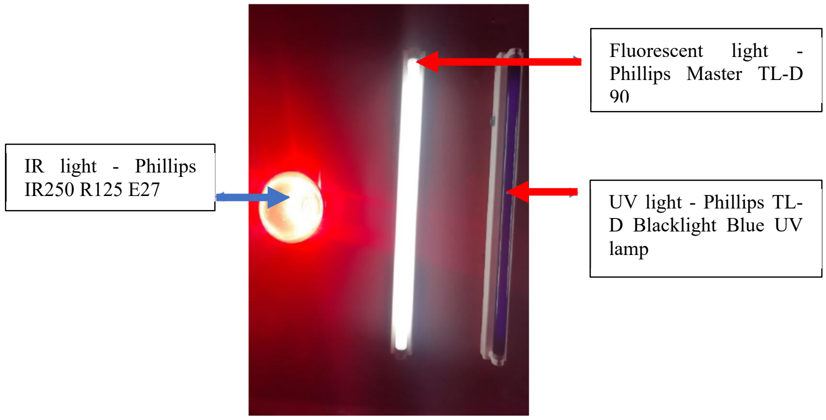

Figure 3-6 Light sources installed in the dark box

Underneath the light sources installed in the test box, a camera and a lux meter were setup in the manner shown in Figure 3-7. The camera was mounted to an adjustable steel frame that can pivot. This enabled the camera to be set up so that any angle and height required (within the limits of the test box) could be achieved for all experimental methods. This also enabled the focussing and relative distance adjustments to be made without changing the zoom on the lens, keeping the setup of the camera itself constant. The lux meter was placed that it could measure from the side of the object placed on the block. This was done in order to keep the view path between the camera and the object being tested unobstructed.

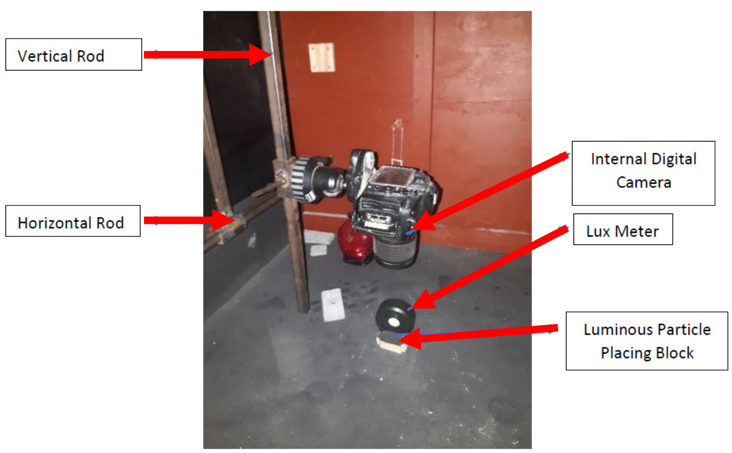

Figure 3-7 Sensor setup in dark box

Once the camera was set up (as described in Section 3.3.1), a series of images were captured with no light on in the test box. The images were then exported to the image processing software, where the brightness of the area surrounding the demarcated test area was determined. This was done as an additional calibration step to account for any light reflectance or background light still present in the dark box. The average value of the ninetieth percentile brightness of all the pixels in the test area was then stored and used as an indicator what the relative 0 cd/m^2 for the test box is. The average ninetieth percentile value was determined to be 0.0234 cd/m^2.

3.2.2 Field tests

Some of the experimental methods required an environment outside the dark test box, to enable measurements from further distances, or light conditions which were not available in the test box. Three additional light sources were used in a field test manner, as the test simulated real life conditions. One of the lights was a streetlight. The streetlight used for this study was a 7 m high LED (slim) streetlight with a cool white light emission. The streetlight was chosen randomly from the collection of available streetlights near the laboratory where the majority of tests were conducted. Figure 3-8 shows the streetlight used for the experimental method. The second light source used in different experimental methods was the sun, as the sun would serve as the main excitation energy source if the concepts were to be implemented in the outdoor environment. When the sun was used as an excitation source, the test specimen was always placed in direct sunlight with no obstruction between the source and specimen.

Figure 3-8 LED street light used

The weather conditions for both the night test and daylight test were measured and captured by a weather station (Sonbesie weather station) directly above the Stellenbosch University Civil Engineering structures laboratory, in which the tests were conducted. The station provides minutely updates on weather conditions, which can be acquired from the weather station website (weather.sun.ac.za) (Meijers, 2020).

Some experimental methods required an environment with low light conditions where the test specimen could be located further from the sensor equipment than was possible using the test box. For the purpose of these experiments a single-track farm road was used, which can be seen in Figure 3-9 during day time light conditions. The light conditions after sunset were such that low artificial light pollution was present, with no street lights on the road and being an adequate distance away from other forms of artificial light. When conducting field tests in this environment, the same camera was used as described in the dark test box. To ensure stable recording of data or images, the camera was placed on a sturdy tripod which was placed in desired locations. When conducting tests in this environment, the additional light source used (third light source) was an Extreme Lights 6 LED 3000 lumin (2013 edition) bicycle light (referred to as the flashlight in this study).

For each experimental method that required field test environments, the weather and light conditions were recorded and mentioned in the relevant description of each method.

Figure 3-9 Single track farm road during daytime

3.2.3 Stable light source box

For the transparency measurements discussed in Section 3.3.5, a stable light source was required. For the light source, a light emitting diode (LED) bulb was used. The bulb was mounted inside a 200 × 200 ×200 mm wooden enclosure, which can be seen in Figure 3-10. Twenty mm thick plywood was used for the wooden enclosure. When a transparent material was tested, the material was placed in a relevantly sized hole drilled in the top of the enclosure. The drilled holes were each centred over the top of the light source for consistency in light angles reaching the holes. The light was placed in an enclosure to ensure that the light reaching the lux sensor, which would be held on the outside of the enclosure over the hole, is only the light traveling through the hole or through the medium being tested. The lux sensor used in this setup is the same sensor discussed for use in the dark test box.

The enclosure was used only in the dark box to ensure no other light source could influence the measurements.

Figure 3-10 Stable light source with enclosure

3.2.4 Oxygen permeability index

Figure 3-11 illustrates the relevant equipment required for the oxygen permeability index (OPI) test. For this test setup, various components are required such as: the flexible sleeve, the metal collar, the cylinder assembly and a pressure sensor of some sort. In this test a large compressed oxygen container is used to supply pressurised oxygen. The pressure gauges are used to determine what the pressure inside the test cylinder is. The pressure inside the test cylinder can be adjusted with the aid of an assortment of valves. Once the pressure was as required, an automated data recording system monitors the pressure in each test cylinder over time. After the completion of the test, the data can be extracted and used to calculate the OPI of a specimen. The volumes of the test cylinders can be seen in Table 3-1 for test cylinder 1 to 4 (left to right in Figure 3-11). For each test three specimens were tested to have a statistically acceptable average value to compare.

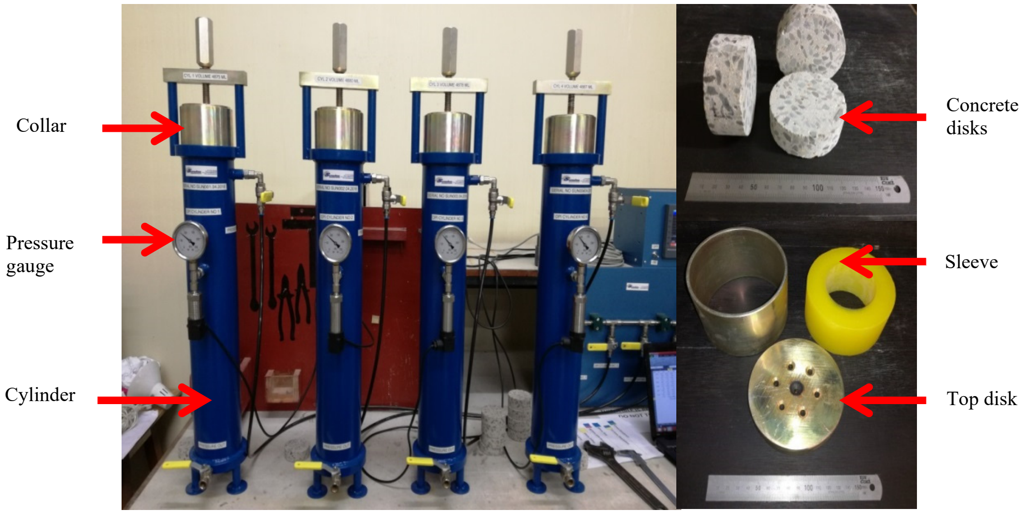

Figure 3-11 OPI test setup

Table 3-1 Cylinder volumes

Cylinder number	Volume	Used during tests
1	4875 ml	Yes
2	4880 ml	No
3	4878 ml	Yes
4	4887 ml	Yes

3.2.5 Curing environment

In order to have comparable values from the test methods, another important factor to keep constant would be the curing conditions of the prepared specimens. For this study two environments were used to cure specimens in, depending on the requirements of the test method considered. These two environments include a climate-controlled room and a temperature-controlled curing tank. The climate-controlled room has a constant temperature of 26.5 °C and a 60% relative humidity. The curing tank has constant temperature water, 24 °C, that is circulated through the tank. The use of constant curing environments ensures that specimens which are compared to one another have been exposed to the same conditions, thus eliminating the environment as an influencing factor in results.

3.3 Measurements

3.3.1 Camera

A lumens sensor is a highly specific and expensive piece of equipment, which was outside the budget for this study, and was not feasible to be acquired as no other experimental setups in the laboratory requires such a sensor. Thus, for the purpose of this study, a different sensor had to be considered, and after research was done, a camera seemed to be applicable for this study. Before using a camera as a light sensor, the difference between illuminance and luminance needs to be understood. According to Hiscocks (2014) the definition of illuminance is the light measured that is falling on a surface, which would be measured in Lux. The definition of luminance is the amount of light which is emitted by a light source, and this is what the human eye perceives as the brightness of a light source, measured in candela per square meter (cd/m^2) (per area of light source). Hiscocks (2014) explains that when a digital camera takes a picture, the image has pixel values which then represent the luminance of the original scene, and taking this into account it can be argued that a camera can be used as a luminance sensor. This is done taking a picture of a light source with a known luminance which then gives a reference point for the next images to be analysed, and the camera to be calibrated, such that a brightness value can be determined.

Setting up the camera calibration to convert luminance to pixel value uses a pre-setup equation, Equation 3-1.

$$N_d = K_c \left(\frac{t\,S}{f_s^2} \right) L_s \qquad \textbf{Equation 3-1}$$

With:

N_d Digital number of pixels in the image

K_c Calibration constant for the camera

t Exposure time

f_s Aperture number

S ISO Sensitivity of the film

L_s Luminance of the scene in candela per square meter

The maximum number of available pixels in the image is determined by Equation 3-2.

$$N_{max} = 2^B - 1 \qquad \textbf{Equation 3-2}$$

Where B is the bit value of the image, i.e. 8 bit or 16 bit.

However, as the lens of the camera is a curved surface, the amount of light received at the edges of the lens, is slightly lower than the light in the centre of the lens, the effect is called vignetting (Hiscocks, 2014). To account for this effect, it is recommended that the source which is being measured, should be as close to the centre point of the lens as possible and to calibrate the camera, a flat surface should be photographed to ensure the light is equal over the entire lens, which bypasses the vignetting effect (Hiscocks, 2014).

Before starting to use the camera as a sensor it is important to consider what image file format to use, of which there are two types. These two types are raw and compressed, of which the raw format stores the exact pixel values directly as the sensor captures them, whereas the compressed format compresses the pixel values to reduce the file size of the image, and to smooth out the lines between pixels. For this application of measuring the luminance with a camera, it is important to use the raw image format to ensure that the accurate pixel values are used as captured by the sensor. A Tagged Image File Format (TIFF) is a universally used format to store raw images. According to Hiscocks (2014), when the image is saved as a TIFF format in colour format, it has to be converted to monochrome before using it to calculate the luminance value of the image. For the camera that is used in this study, the format is Nikon Electronic Format (NEF), which is similar to the TIFF format.

The lens attached to the camera is able to zoom, however it is ideal to keep the zoom setting constant to eliminate any possible changes, especially in the image processing stage. The luminance of a source is measured in cd/m^2 and the luminous power in candela is measured in lumens per steradian. The zoom changes the area of the sensor exposed and the angle of measurement in such a way that there is no resultant effect and therefore, if the zoom is altered the results would not be influenced (Hiscocks, 2014).

Using a camera as a light sensor introduces inaccuracies in the results which is an inherent problem depending on the quality and sensitivity of the image sensor. Seeing that a good quality camera is used, with a reliable image sensor, the inaccuracies are not significant. Furthermore, as long as the measurement method is constant for all tests, the data is comparable.

The setup was configured to accommodate a Lux meter next to the luminescent material, of which the measurement was recorded at the same time that the photos were taken of the luminescent material. This was done to be able to relate the values of the photos to that of the lux meter as an additional check.

Table 3-2 gives the details of the camera and the settings used in this study for the test conducted in the dark box.

Table 3-2 Camera setup

Camera name	Nikon D7000
ISO	6400
F-stop	F/5.6
Exposure time	1/5 s
Focal length	18 mm
Lens type	Nikon DX 18-105 mm
Flash	No

Initial tests were conducted by placing the camera at a set distance away from the luminescent material on a stable mounting. The initial tests were conducted to evaluate the exposure time influence on the luminescent material, to determine the difference in output with varying exposure times.

The camera was set up in such a manner that the luminescent material was in the same centre position in the view-finder of the camera. The camera was placed at a distance of 150 mm away from the surface on which luminescent material was placed.

When attempting to determine a calibration constant for the camera according to Equation 3-1, a candle was used as a reference point, as well as a LED bulb. However, the brightness compared to that of the luminescent material posed a problem as both reached the maximum pixel value (together with flooding the lens with light) on the settings to be used to photograph the luminescent material. The solution to this problem was finding a light source with a known luminance closer to the output of the luminescent material. A laptop screen (Lenovo T460) was used on the lowest brightness setting to accomplish this. With the screen having a lux value of 0.47 compared to a lux value of 10.76 of a candle.

To extract a quantitative measurement from the images captured, MATLAB R2018b was used to process the images once the tests were done, of which the programmed code is attached in Appendix A. The steps followed were to load the image into MATLAB, then convert the image to grey scale, choose the relevant pixels to analyse, process the pixels and provide an output of a pixel value. The pixel value would be on a grey scale of 0 to 255, with a brighter pixel relating to a higher pixel value. This pixel value can then be converted to a luminance value using Equation 3-1 and also be compared to a lux value measured by the lux meter. Initial tests were conducted by selecting certain pixels of the images that were on a luminescent aggregate; however, this was changed to rather determine the average pixel values over a specified area. By doing this, the entire light emission of the aggregate can be determined, with all the pixels being taken into account. The average amount of light per area is a better comparative value than only certain pixel values, as it reduces the error caused by slight movements of test specimens, if any should occur between tests.

3.3.2 Lux meter

According to Hiscocks (2014) it is possible to determine the luminance of a light source at some distance away from the source by converting the illuminance value. There is however an inaccuracy in this method as the radiation pattern is unknown which influences the results as the radiation pattern is assumed as a sphere, thus the measurements from the lux meter can only be used as a check for the measurements obtained from the image processing. Nonetheless, a light meter produces a result in lux, with,

1 lux = 1 lumen/m^2

And light energy emitted by a source is measured in candela, with

1 candela = 1 lumen/steradian

And

$\text{Steradian} = \Omega = \frac{A}{r^2}$

Where Ω is the solid angle in steradians, r is the distance from the light source and A is the area of an imaginary sphere on which the light falls. For this application, one can use the surface of the spherical lux sensor.

Resulting in Equation 3-3, as follows:

$$\frac{candela}{m^2} = \frac{Lux}{\Omega}$$ **Equation 3-3**

An Epsilont 2000 (MS6612) lux meter was used in this setup, with a resolution of 0.01 lux, a range of 0 to 200000 lux and an accuracy of +3%.

3.3.3 Light emission

Exposure time

It is important to determine the influence that different light sources and exposure times have on the brightness and brightness decay of the luminescent material, as it determines the applicability of the material in different environments. Firstly, the influence of the exposure time on the brightness decay was determined by having a single aggregate, seen in Figure 3-12, be exposed to different periods of light exposure. This entailed exposure of 15 minutes, 1 hour, 2 hours and 8 hours. Before each test was conducted, the aggregate was stored for at least 8 hours with no excitation energy present. The aggregate was placed as specified under the camera, preventing external light to charge the aggregate. Once the aggregate was on a demarcated location, an electrical timer switch was used to turn on a UV light in the dark box, keeping it on for the specified time period after which the light was switched off by the timer. This was when the camera immediately started capturing images on a 10 second interval basis for a time span of 30 minutes, whereafter the time interval was changed to 3 minutes for the remainder of the 8 hours. The images were then exported to the image processing software to determine the brightness of the aggregate. Each exposure time test was carried out three times.

Figure 3-12 Single luminescent aggregate

Interval re-exposure

To attempt to reduce the brightness decay, or in other words to extend the time which a higher brightness is seen, an attempt was made to re-introduce energy to the aggregate while brightness decay was still in progress from an initial exposure. This was done by placing the same single aggregate on the demarcated spot in the dark box and exposing the aggregate to 15 minutes of UV light. After the initial exposure time had passed, the electrical timer switched the light off and the camera started to capture images every 10 seconds. After 15 minutes had passed with no light exposure, the UV light was turned back on for 60 seconds. This was repeated a further two times.

This experiment was done in order to simulate how the brightness of the aggregate would decay if implemented in an environment where the aggregate was excited on an interval basis, receiving pulses of energy when the brightness decayed too far.

Light source

Once the influence of exposure times was determined, the next step was to expose the same aggregate to different light sources, which were mentioned in Section 3.2.1, to determine the influence on the brightness decay over time. A constant exposure time of 1 hour was used to be able to have comparable results. The experimental procedure followed the same order as the previously mentioned procedure for the exposure time influence test, with the only difference being the use of different light sources in the test box instead of using a constant light source, and keeping the exposure time constant. Five different light sources with different UV outputs were used, being the three installed in the test box and additionally the sun, and the streetlight. Preliminary results indicated that all further tests involving light source exposure had to be conducted in the test box using the UV lamp as it has a consistent UV light output, compared to the sun which has a variable UV light output, and the fact that UV light is the common wavelength which excites the material.

To test the influence of a streetlight, the aggregate was placed directly under the streetlight for the required 1-hour period, after which it was moved directly into the test box, as swiftly as possible, where the camera would have started to capture images as described previously. This would give a good indication of how the luminescent material would absorb energy if it was to be used in sidewalks. Additionally, the influence of night time exposure was tested to determine if the luminescent material was able to charge during the night, extending the time the material can luminesce. The weather conditions for the streetlight exposure were consistently chosen as warm evenings with a clear sky.

Similarly, for the sunlight exposure, the aggregate was placed in direct sunlight with no obstructions, with the weather conditions being recorded. After the required exposure time, the aggregate was moved into the test box as swiftly as possible after which the camera started to capture images, as described previously, of the luminescent aggregate. The weather conditions for the sunlight exposure were consistently chosen as warm days with a clear sky and a peak UV emission of around 25 Watt per square meter.

Luminescent aggregate

A small slab was cast with a single aggregate surrounded by mortar paste, seen in Figure 3-13 which illustrates the slab under fluorescent light and under UV light. The mix proportions of the mortar paste are not significant, as the only purpose was to prevent light from reaching other surfaces of the aggregate. The dimensions of the concrete slab were 111 mm x 50 mm x 10 mm. Once the mortar paste hardened, the slab was sanded down on both large surfaces to ensure the luminescent aggregate was exposed on both sides. The slab was then placed in the dark box for at least 8 hours to ensure any excitement energy was dissipated. The slab was then placed on the demarcated area to be exposed to a UV light for 1 hour, after which the light was turned off, and the slab was then turned over. The camera started to capture images at 10 second intervals for a total of 100 seconds. These images were then uploaded to the image processing software, to establish if the light energy is absorbed through the aggregate, as only one side of the slab was exposed to UV light while the other side was measured.

The test was repeated and the brightness of the exposed side was measured as a comparative value. This determined if the aggregate can be charged from the one side and efficiently luminesce to the other side, also explaining how the light energy is absorbed and emitted by the aggregate.

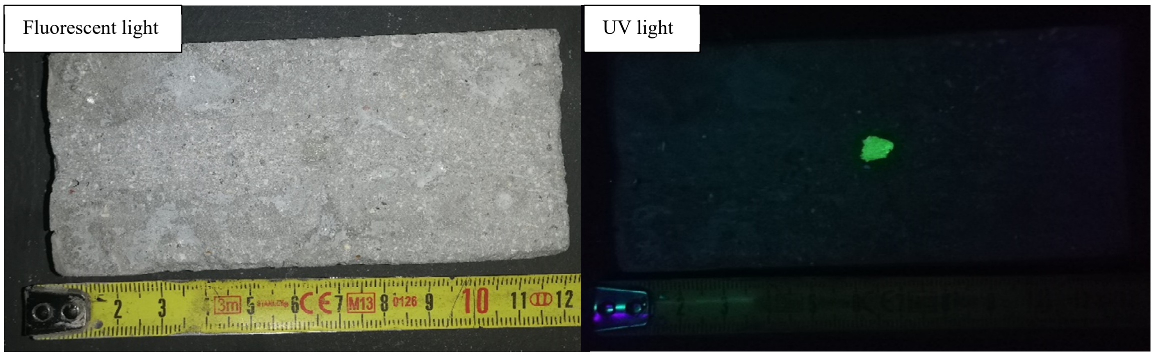

Figure 3-13 Single aggregate in thin slab under different light sources

Luminescent powder

The luminescent powder used for this experimental setup is a very fine powder. When attempting to implement the luminescent powder, different methods were tested. This included merely dusting the powder onto the wet concrete, and secondly mixing the powder into the concrete paste. Both methods posed their own problems. While the dusting of the powder had a good amount of exposure to an energy source, the exposed powder not directly in contact with the concrete paste was not fixed to the surface, resulting in the powder being removed when disturbed. Mixing into the concrete resolved this problem, however for this method few of the luminescent particles were exposed to the surface.

A cement paste was mixed with a water to cement ratio of 0.45, not adding any aggregates to the mix. A mass of 11,1 g of luminescent powder was added to the paste per cube mould volume, the mould having dimensions of 50 mm × 50 mm × 50 mm. The mass of luminescent powder added to the cube mould relates to 6.82% of cement mass per mould cube. A cube was cast only containing the cement paste as a reference, and another was cast containing the luminescent powder. The cubes were left to cure for one day in a climate-controlled room, whereafter they were removed from the mould and placed back into the climate-controlled room until testing. The curing time of the cubes were not recorded as no mechanical tests were conducted on the cubes, the curing was only done to ensure a stable cube which could be handled. The cubes were placed adjacent to each other in the dark test box. The cubes were then exposed to a UV lamp for 1 hour. After an hour of exposure, the lamp was switched off and the capturing of images started. Ten images of each cube were captured with a time interval of 10 seconds. The limit on the number of images captured was placed as a rapid decay in brightness was observed during a trial. The images were exported to the image processing software to determine the amount of light emitted by each of the cubes.

3.3.4 Perception

The main focus of the implementation of the different materials into the concrete is to improve the visibility of the concrete in low light conditions. To determine if the concrete is in fact better visible, it is important to test the perception of implemented concepts, especially with human participants.

Recognizable object

To determine if the luminescent aggregate is capable to produce light in such a manner that an object can be recognised from a distance, the following experiment was undertaken. According to the design prescriptions provided in Road Traffic Sign Manual (SADC RTSM) (Bain et al., 1998) which can be seen in Figure 3-14, a road sign was made using luminescent aggregate, as the road sign is an object that should be easily identifiable. Seeing as the sign was made from the luminescent material used in the production of luminescent concrete, the signs can be incorporated into concrete structures used along the side of roads such as barriers, bridge structures etc.

For this experimental setup a W405 sign, Figure 3-14 together with Table 3-3, was made which is used to indicate a sharp curve in the road layout. This was chosen for reason of the ease of recognition and low amount of detail required. Using the prescribed dimension for a sign in an area with a speed of 100 to 120 km/h was seen as an applicable choice, as the application of such road signs are in low light condition environments, which would generally be on rural or national roads with a speed limit mentioned.

The luminescent aggregate was placed on the inside of the arrow lines, as seen in Figure 3-15, at a distance of 50 mm from each other, resulting in a mass of 0.126 kg being used, costing R50.40 (R400/kg). To limit wasting the luminescent aggregate, the aggregate was attached to the surface of a board with removable glue. The board was exposed to an excitation source, being the flashlight, which was used at time intervals of 30 seconds, as the test was conducted. The test entailed the placement of the luminescent sign at distance intervals of 25 m intervals up to 100 m. The sign was photographed on a setting, Table 3-4, which captured the environment similarly to the human eye, resulting in comparative images in a low light environment. The similarity of the image to how the environment was perceived by the human eye was confirmed by two bystanders.

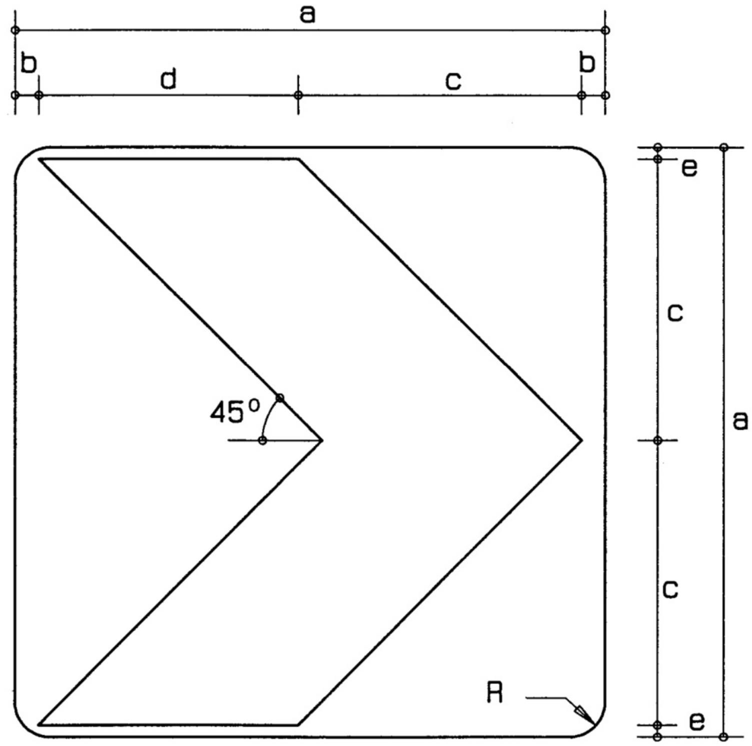

Figure 3-14 Road sign (Source: Bain et al., 1998)

With:

Table 3-3 Road sign dimensions (Source: Bain et al., 1998)

a	b	c	d	e	R
600 mm	24 mm	288 mm	264 mm	12 mm	36 mm

Figure 3-15 Luminescent aggregate arranged on a board

Table 3-4 Camera setting to capture images for recognizable object test

Camera name	Nikon D7000
ISO	6400
F-stop	f/22
Exposure time	10 s
Focal length	18 mm
Lens type	Nikon DX 18-105 mm
Flash	No

Perception of object

For the sake of safety during traveling it is important that an object can be recognised from a safe distance for the individual traveling to take informed action. It was important to have individuals take part in a field study to determine from what distance an object can be recognised in an applicable surrounding. Four participants (limited available) took part to indicate when the sign in Figure 3-15, which was a known and recognizable object, was not clear anymore. This is an indication if the material would be beneficial to improve the visibility of known objects. The field experiment followed the following procedure: the unexposed sign was placed at a distance of 25 m from the participants, after which it was exposed to excitation energy for 30 seconds from the flashlight, after which the participants increased their distance from the sign until the sign was no longer observed as a known object. This distance for each participant was recorded, after which the sign was exposed to a further 30 seconds of light to revive the excitation to starting brightness to allow the participants to state if the sign can once again be easily recognised.

The environmental conditions were as follows: after dark on a low light pollution farm road, surrounded by vineyard, with a clear sky and moon phase between full moon and third quarter, while the moon was low on the horizon.

Road side illuminating

Using the luminescent aggregate, and a spacing of about 1 m along the edge of a curved single road, the aggregate was placed on the edge surface of the road. This served as an indication of the curvature of the road during the night. Three conditions of lighting of the road was photographed, being during the day, at night with the luminescing aggregate alongside the road and finally the road at night with the luminescent aggregate removed. The three conditions can be visually compared to determine the effectiveness of having the edge of the road illuminated by the luminescent aggregate. The images were captured during a clear, no cloud, autumn day at 2 pm, and during the night of that day with no street lights, in a low light pollution environment at 7 pm, with no moon visible in the sky. The luminescent aggregate was only exposed to sunlight during the day and no additional light source was used to excite the material.

3.3.5 Transparency

For this study, different transparent materials were tested to determine the efficiency of light conduction through each medium, to be able to create light pathways into the concrete for the applications of having transparent concrete and additionally, have light energy be conducted to luminescent material imbedded in the concrete.

Three different materials were used for their transparency properties; resin material, plastic optical fibre, and lastly glass.

Resin

Testing of the different resin materials required casting the resin material into useable objects. Each resin was mixed with the indicated amount of hardening agent, then decanted into a clean syringe for ease of introducing into mould without air bubbles. A small thin 5 mm (inner diameter) paper cylinder (straw) was used for this process. The mould was placed over the tip of the syringe. With the syringe pointing upward, the mould was slowly injected with resin until the desired fill level was reached. Once the fill level was reached, both ends of the mould were clamped shut in such a manner that the entire volume of enclosed mould was filled with resin. The resin filled mould was left upright overnight in a 24 °C curing room to harden. Once hardened, the mould and resin assembly were cut at a desired length (20 mm), lightly polishing the cut ends of the resin, forming a translucent prism.

The light conductivity of the resins was tested by determining the amount of light lost when the light has to travel through the resin. For the measurement of this, the enclosed stable light source was used. A 5 mm hole was drilled through the top of the enclosure, and a lux sensor was placed on the other side of the hole. The first step was to measure the light received with no disruption of the light flow through the hole, i.e. only a 5 mm hole straight through the wood. After which the prism of cast resin was placed in the hole in the wood between the light source and lux sensor, measuring the light reaching the sensor. The loss of light was then be determined by means of Equation 3-4.

With:

$$\%loss = \frac{A_u - B_r}{A_u} \times 100 \qquad \textbf{Equation 3-4}$$

A_u being the unrestricted light flow and B_r being the restricted light flow.

It was important to determine if the resin would conduct UV light, as it is required for the intended implementation of the light paths. This was done by using the UV sensitive luminescent aggregate. The aggregate would luminesce if UV light passed through the resin prism. With the prism inserted into the wooden plank, the LED light was placed on the one side and an unexcited luminescent aggregate was placed on the other side of the prism. The aggregate was exposed to the light traveling through the resin for 1 minute whereafter the light was switched off. The resulting luminescence was recorded.

These tests determined the amount of light lost through the resin, and if the material was able to conduct UV light. The suggested application for such a combination is that the luminescent aggregate can be energised through UV light that passes through the resin, which means that the luminescent material can be imbedded in the concrete and only the resin needs to be exposed to the surface. Alternatively, if it is found that the resin does not let enough UV light pass through, but only visible light, the entire "system" can be switched around. This implies that the luminescent material is exposed to the surface of the concrete, which enables it to be energised by UV light, and the resin is then used to conduct the emitted light, falling in the visible spectrum, through the concrete to the other surface on the concrete, combining the concept of transparent and luminescent concrete.

Fibre optics

As mentioned, fibre optic material was also considered as a possible transparent material to implement. This was done with the following setup. Again, the enclosed stable light source was used for these measurements. The measuring of the light was done by placing the lux meter over the hole. This was done for a 2 mm hole and a 0.7 mm hole through a 20 mm wooden sheet.

After the baseline was determined, a 2 mm diameter fibre strand of 1000 mm length was placed in the hole. The brightness of the light passing through the strand was measured. To ensure no side entering/exiting light affects the results, all the strands used were covered in electrical insulating polyvinyl chloride tape. This was done as an additional step seeing that the fibre core is already covered by a cladding. Figure 3-16 shows the fibre after the tape was added around the outer surface. The ends of the fibres were sanded down to a smooth finish to ensure the same light influence angle was present for all the fibres. Additionally, a 0.7 mm fibre was used in a similar way to determine the influence of the thickness of the fibre, on the light conduction. Multiple readings of five were recorded to obtain an average reading for each to take into account small movements of the lux meter or tip of the fibre. With regards to the placement of the fibre in the drilled holes, it was ensured that the fibre end does not pass further through the drilled holes than the inner brim. This was done to ensure the equivalent amount of angled light beams reach the fibre compared to only the drilled hole.

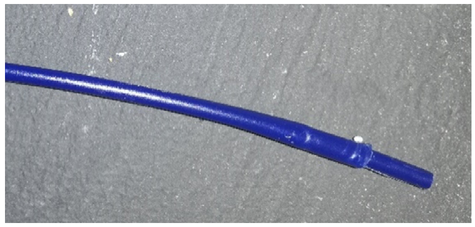

Figure 3-16 Insulated POF (2 mm)

As with the resin light conduction test, Equation 3-4 was be used to determine the amount of light lost when the light had to travel through the fibre material.

Optical fibres transmit light through a medium; however, the medium used does not necessarily transmit all wavelengths of light, by design or by default of the material type. Some material degrades under UV light; thus, the material is designed to be UV resistant to prevent this degradation. When considering a fibre optic, or any other material, to use in this study, it has to be ensured that material does indeed allow UV light to pass through as that is the wavelength needed to excite the luminescent material which is needed for some applications. If the material does not transmit the UV light, the luminescent material would not be excited if it is connected to a fibre and the material would serve no purpose.

When the optical fibres are tested, a baseline test to determine the amount of light the material conducts throughout the length should be conducted, to establish the amount of light energy lost. This would be an indication of the amount of light lost from the luminescent material. This test method should be applied to all transparent mediums which would be used. The test should be conducted by measuring the light emission from a light source at a direct angle. After this, the material should be placed in a divider with the material inserted, which would prevent any light from reaching the sensor that is not passing through the material.

Glass

To attempt to produce a transparent concrete, the coarse aggregates in a concrete mix were replaced by glass aggregates. If it could be achieved that the glass particles are in direct contact with one-another, light should be able to travel through the contact surface between the particles, creating a light pathway through the concrete.

Clear glass aggregate, of size 9 mm, was placed in a 50 mm × 50 mm × 50 mm mould. The glass was added to the mould while the mould was placed on a vibration table, ensuring that the particles have a close packing. Once filled, the top was closed with a non-stick rigid cover with an injection hole in. The cover was clamped down before a cement paste was added to ensure the glass stays in direct contact, as shown in Figure 3-17. The clamps stayed on the mould until the paste hardened. A highly flowable cement paste was required to enable injection into the mould to fill the pours between glass aggregate. An additional cube was made by slowly pouring the paste over the compacted glass aggregate, to allow the paste to seep into the pores, rather than injecting the paste. A water cement ratio of 0.45 was used, and as no sand or stone was added, the consistency of the mixture was sufficient. Once the cubes had hardened for 1 day, they were removed from the moulds and stored in a climate-controlled room for a further 6 days to ensure sufficient hardening. Once the curing time passed, the top and bottom of the cubes were polished to expose glass aggregate surface. The polishing was done with a high rotational speed, diamond tip polishing machine.

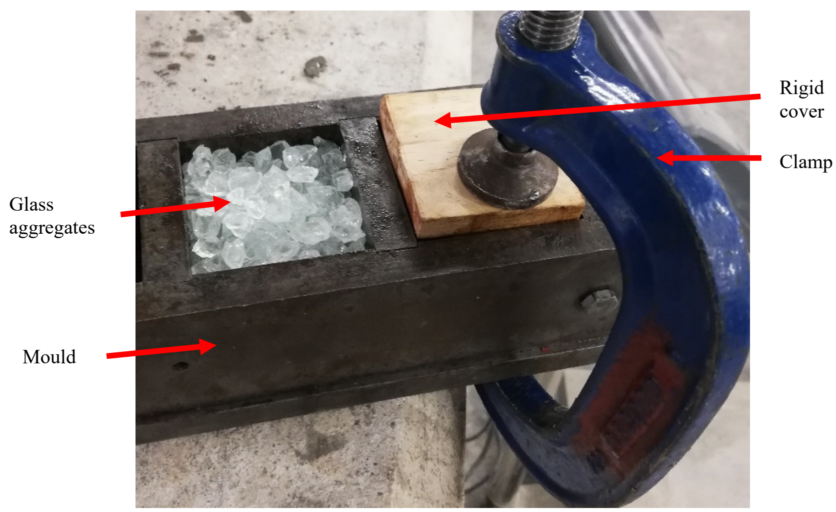

Figure 3-17 Glass aggregates in mould

Using a lux meter and the stable LED light source installed in the wooden enclosure, the light passing through the cube was measured. This was done by means of recording the lux value of the light source passing through a 28 mm diameter hole in the wood cover, then moving the cube between the light source and the lux meter and once again taking a reading of the light by placing the lux meter on the surface of the cube. As Section 3.3.5 described, Equation 3-4 can be used to determine the amount of light lost with the cube in place.

As the purpose of this experiment was to only produce a transparent concrete, mechanical properties were not tested.

No fines concrete resin cast

When considering the incorporation of light pathways into concrete, a no fines concrete was considered. This was seen as a potential method to incorporate light into a concrete unit, by means of having air pathways into the unit. For an additional measure to produce translucency, glass aggregate was used instead of having normal stone as the coarse aggregate. The mixture comprises of a water to cement ratio of 0.38 to form the paste to bind the aggregate. The mass of glass aggregate was such that it was 8 times the mass of the cement used. The mixture was mixed until all the coarse aggregates were coated with paste, after which the mix was decanted into a 50 mm × 50 mm × 50 mm mould. Two units were cast, one filling the mould (1), the other only reaching thickness of 18 mm (2). A curing time of 3 days in a climate-controlled room was given to allow for sufficient strength gain before demoulding. The units were stored in the climate-controlled room until the light conduction test. The curing time was more than 28 days; however, it is not of importance as mechanical properties were not tested. Using the stable LED light source and the 28 mm hole, the reference lux value was recorded, similar to the glass unit testing. Units 1 and 2 were both tested by placing the unit over the hole, placing the lux meter on the opposing surface to the hole and recording the value.

After the aforementioned was completed, ultra-clear casting resin was mixed and added to the units. This was done by placing the units back into the moulds, and casting the resin over the unit. This was done slowly to allow ample time for the resin to fill the cavities entirely. The units were placed in the climate-controlled room for 7 days to allow for complete curing. Once the units were removed from the moulds, seen in Figure 3-18, the same translucency test was repeated for each unit.

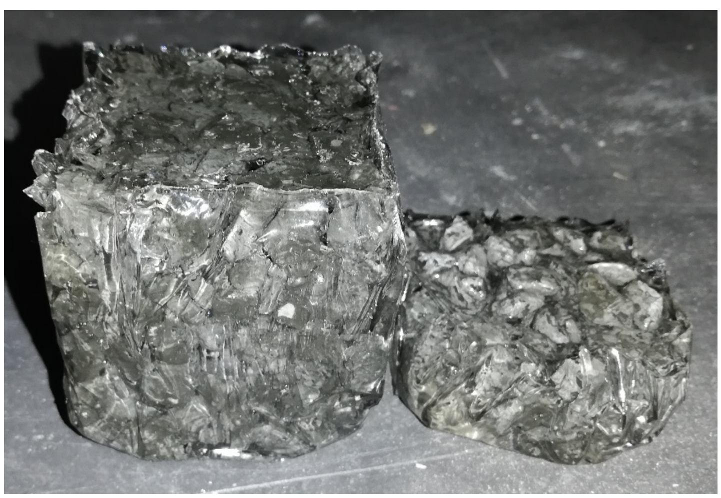

Figure 3-18 No fines concrete with resin filled pores

3.3.6 Durability

It is important to consider what the influence would be on the durability of concrete if either the luminescent aggregate or transparent materials are added to the matrix. This was done by conducting an oxygen permeability index test or OPI test, in accordance with SANS 3001-CO3-2 code (South African Bureau of Standards, 2015), with one deviation from the specified code. The deviation being the use of the top section of the concrete cube instead of cutting the disk from the centre part of the cube. This was done as the implemented material will mostly have an effect on the top section of the casted concrete as the material is added to the surface of the concrete where it is visible.

A concrete mix, with mix proportions described in Table 3-5, was prepared. Once the concrete was sufficiently mixed in a 25-litre pan mixer, it was decanted into 100 mm ×100 mm ×100 mm moulds. While the concrete was still in the fresh state, luminescent aggregates were placed on the surface with a distance of around 20 mm between each aggregate centre point, seen in Figure 3-19, and floated into the surface with a trowel, while on a vibrating table. The floating was done with limited sideways movement to attempt to limit the disturbance of the placement of the aggregates. Additionally, reference cubes were also cast. Three samples of each were made to ensure testing has a statistical average value, of which the OPI values were compared to the reference mix.

Table 3-5 Concrete mix proportions for OPI tests

Material	**Mass (kg/m^3)**	**Relative density**
Water	220	1
Cement (CEM II 52.5 N)	415	3.14
Stone (13.2 mm Greywacke)	851	2.8
Sand (Philippi)	901	2.62

Figure 3-19 Luminescent aggregate OPI cubes

For the durability of fibre optic concrete, similar sized cubes were cast with the same concrete mix design, Table 3-5. However, instead of placing the luminescent material on the surface of the concrete, a fibre optic strand was inserted into the concrete matrix, in the centre of each cube. This was done while the mould was placed on a vibrating table to ensure even interaction with the matrix along the length of the fibre. The fibres were left to protrude out of the surface, as seen in Figure 3-20, which was removed once the concrete was cut into disks. Cubes were cast with two different thickness fibres inserted, being 0.7 mm and 2 mm. Three samples of each addition were made to ensure testing has a statistical average value, of which the OPI values were compared to the reference mix described.

Figure 3-20 POF cube for OPI

After one day in a climate-controlled room, the cubes were removed and placed in a curing tank for the remainder of 28 days. After 28 days the cubes were removed, after which using a 70 mm diameter core drill, each cube was cored. The top 25 mm of each cube was cut to form disks to be used in the OPI setup. The disks were placed in a 50 $°C$ oven for 8 days to completely dry the samples. The dimensions of each sample were recorded for later calculations. Section 3.2.4 discussed all the relevant equipment used during the conduction of the OPI test. Each disk was placed in a sleeve, then both were inserted into a collar with a top disk covering the assembly. The assembly was then placed on a cylinder, after which the bolt head was tightened to create a sealed system. Each cylinder was flushed with oxygen for 5 seconds, after which the outlet valve was closed to achieve a cylinder pressure of 100 kPa $\pm$ 5 kPa. Once the required pressure was reached, the inlet valve was closed to ensure the oxygen in the cylinder can only escape through the concrete disk. Every 5 kPa pressure drop time period was recorded until 6 hours elapsed or 50 kPa was reached, indicating the end of the test.

Once the physical test was completed, the recorded data was used as input for equations to finally calculate the OPI value of each disk. Equation 3-5 calculates the OPI.

$$OPI = -\log_{10} k \qquad \textbf{Equation 3-5}$$

With,

k as the D'arcy coefficient [m/s]

The D'arcy coefficient is calculated using Equation 3-6.

$$k = \frac{\omega \times V \times g \times d \times z}{R \times A_s \times T} \quad \textbf{Equation 3-6}$$

With,

ω as the molecular mass of oxygen [0.032 kg/mol]

V as the volume of the cylinder [m^3]

g as gravitational acceleration [9.81 m/s^2]

d as the average specimen thickness [m]

z as the slope of the regression line

R As the universal gas constant [8.313 Nm/(K.mol)]

A_s as the cross-sectional area of the specimen [m^2]

T as the absolute ambient temperature [K]

The slope of the regression line in turn is calculated using Equation 3-7.

$$z = \frac{\sum \left(\ln(\frac{P_0}{P_t})\right)^2}{\sum(\ln\left(\frac{P_0}{P_t}\right) \times t)} \quad \textbf{Equation 3-7}$$

With,

P_0 as the initial pressure [kPa]

P_t as the pressure at time t [kPa]

t as the elapse time [s]

3.3.7 Aesthetics

As aesthetics are dependent on the beholder of the object, it is difficult to have a quantitative measurement of the aesthetics of this study. Thus, a five-question survey was set up, and using several participants, the perceived aesthetics of a concrete sample, having included luminescence and transparency, was determined. As the resulting concrete concept will be implemented in environments which have people as observers of the concrete structures, it was thought to be relevant to use randomised participants to deliver their opinion on the aesthetics of the concrete. Appendix B shows the survey used.

3.3.8 Concept combination unit

The possibility exists that the combination of these different concepts investigated could be more effective in creating a concrete unit better visible in low light conditions. To test this, selected materials from relevant concepts were combined to produce a single unit of concrete which can emit luminesce and be translucent. When considering Figure 3-21, it can be seen that 2 mm POF was used to provide light pathways into and through the concrete unit. The POF was also placed such that light would be able to pass straight through the unit, and around a 90° corner. The POF was used to create light pathways to and from imbedded luminescent aggregates (LuminFibre). Some luminescent aggregates were exposed to the surface to receive direct excitation energy which is connected to another surface with a POF strand. The POF strands were held in place during the casting of the concrete mix by means of placing the strands through holes drilled in the side wall of the 300 × 100 × 100 mm mould. The inner surface of the mould was coated with a release agent for easy removal after the concrete has hardened. Resin prisms, with a paper coating, were used in a similar manner as the POF strands. The concrete mix used to cast this unit and a reference unit with no additions, is detailed in Table 3-6.

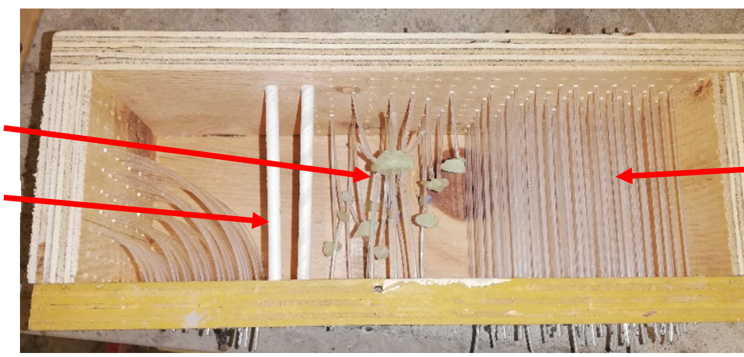

Figure 3-21 Combination unit mould

After the concrete was poured into the mould on a vibration table, luminescent aggregate was scattered, by hand, on the top surface of the concrete and floated into the matrix. Similarly, 1.5 g of luminescent powder was thoroughly mixed with a small amount of concrete before being floated into the top left corner of the unit. The moulds were placed in the climate-controlled room for 3 days to allow sufficient time for hardening before removal from the moulds. After a further 4 days in the climate-controlled room, the surfaces of the units were polished. The polishing of the units was done to create a smooth surface and to ensure both the luminescent aggregates and translucent materials were exposed to the surface. The polishing was done using a high-speed rotational diamond tip polishing machine.

Table 3-6 Concrete mix proportions for combination unit

Material	Mass (kg/m^3)	Relative density
Water	250	1
Cement (CEM II 52.5 N)	385	3.14
Stone (6 mm Greywacke)	875	2.8
Sand (Philippi)	825	2.62

3.4 Test program

The following test program was followed to complete this investigation. The relevant experiments were conducted to characterise the different materials implemented. The influence of different light conditions on the luminescent aggregate was determined to better understand the material behaviour. The aggregate was implemented in a real-world environment to determine how the material behaves once placed in a realistic environment. The different translucent materials were tested to determine their light conduction capabilities. The influence of the addition of different materials on the durability of concrete was determined on the basis of an OPI test. Finally, all the concepts were combined to produce a single unit that has translucent and luminescent properties of which the aesthetic value was determined.

A summary of the test program in the form of an experimental matrix can be seen in Table 3-7.

Table 3-7 Experimental matrix

Category	What is tested?	Focus material(s)
Light emission	Influence of different exposure times on brightness decay	Luminescent aggregate
	Influence of different light sources on brightness decay	
	Influence of interval re-exposure to a light source on brightness decay	
	How light is transmitted through the material	
	Brightness decay of luminescent powder	Luminescent powder
Transparency	Light transmission through a material	POF (PMMA)
		Resin
		Glass
Safety	Visual comparison of distances from a luminescent object	A sign made from luminescent aggregate
	Human perception of a luminescent object	
	Road edge illumination	Luminescent aggregate
Durability	Oxygen Permeability Index	Luminescent aggregate, POF
Aesthetics	Survey on the aesthetic influence of incorporated materials	Concrete unit containing POF, luminescent aggregate, resin

4 Results

In this section the results of the experimental work are presented and discussed. The discussion includes an elaboration on the results as well as the significance thereof. No previous research could be found which tested the same material, under the same conditions as done for the results in this section, showing the brightness decay over time.

4.1 Light emission

In order to better interpret and understand the results presented in this section, Figure 4-1 has been compiled, as an example, from the resulting brightness of three data sets of a single light source, with annotations to provide guidance on what is presented. In Figure 4-1 the luminescent and ground states, as mentioned in Section 2.1.5, are indicated as a dashed and/or dotted line. These lines merely represent an approximation on where the state of excitation is located over the period of decay.

The luminescent state can be defined as the approximate point where the gradient of the resulting curve starts to decrease from above 0.9 to below 0.9 (in the negative direction). The ground state can be defined as the point where the resulting curve connects to the horizontal axis, or the dark box interior brightness line for this study. The interior brightness was determined to be 0.0234 cd/m^2 according to Section 3.2.1. More relevant information to notice on the graph is the transition zones between excitation states, as that is an indication of how long the material stays in the specific transition period, which influences the perceived brightness of the material. These transition between excitation states are gradual processes rather than an abrupt step. For each collection of results shown in this section, the transition zones move according to the amount of energy available to be released.

The last important observation to make is that according to Section 2.1.4, the sensitivity of the human eye (of which the upper limit of the low light sensitivity, 0.003 cd/m^2, is plotted in a red dashed line) is well below the lowest brightness measured for these tests. This indicates that even when the brightness of the luminescent material reached the ground state, it could still be seen in the dark box by the human eye (if the human eye had sufficient time to adjust to the light conditions inside the dark box).

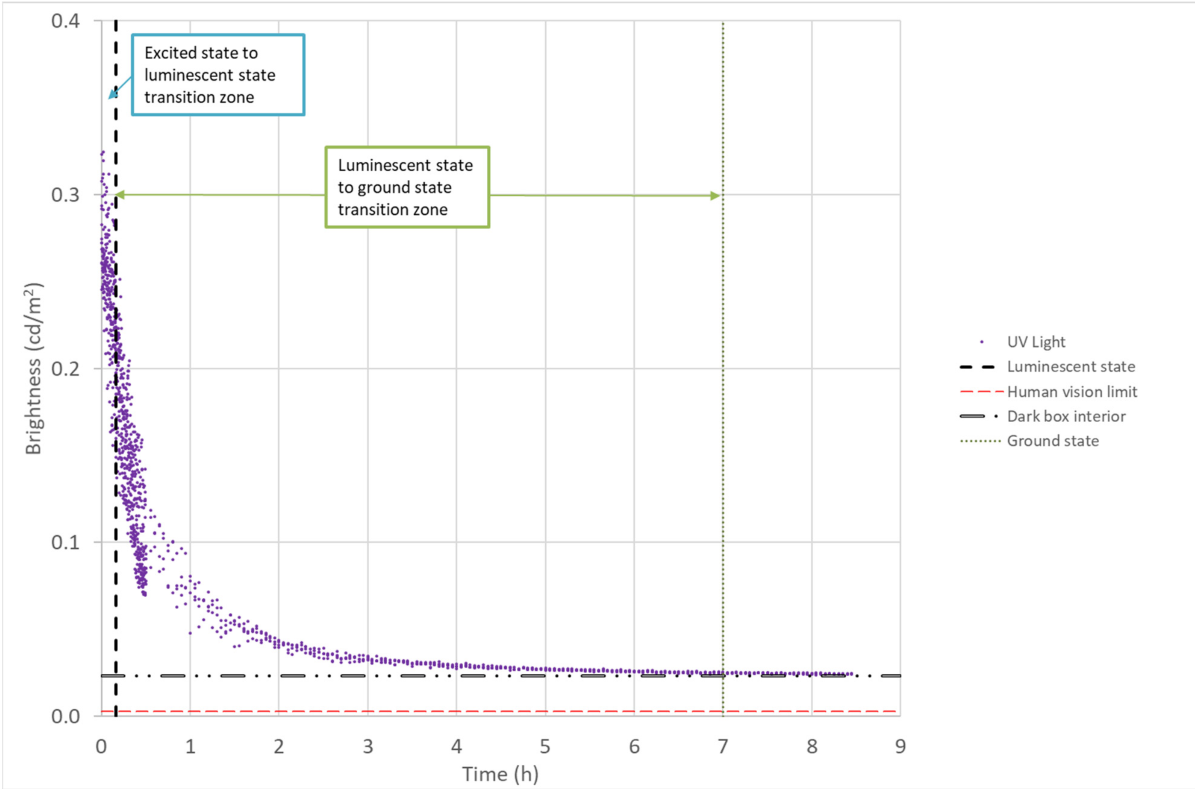

Figure 4-1 Example on how to interpret the results for Section 4.1

A different method to present the results in this section would be to plot the data points on a log-log graph, or in other words a graph with both axes in logarithmic format. This would yield straight lines for each data set. However, for the presentation of the brightness decay of the luminescent material, it was found that simply plotting the datapoints on standard axes yielded a better representation of what is observed during the decay of the material. This being a rapid initial brightness decay followed by a steadier decay over a longer period.

4.1.1 Exposure time influence

As discussed in Section 3.3.3, the influence of different exposure times on the initial brightness and the decay curve of the luminescent aggregate was tested. By combining all the data points of the repeated tests, a best fit curve was fitted to the decay of the material. The graph function which best fitted the data points was found to be a power function. All the fitted curves have a R^2 value close to 0.9, which indicates that all the graphs fit their respective data collection fairly equally, thus the curves are comparable. Figure 4-2 shows the resulting decay of the luminescent aggregate from 0 hours to 8.5 hours. The colour of the data points of each test, 3 for each exposure time, correlates to the colour of the fitted graph. However, as the trend lines are very similar and closely grouped, the difference is unclear on Figure 4-2, thus an enlarged graph of the same data, up to 1 hour, is provided in Figure 4-

3. As can be seen in Figure 4-2, the majority of the decay of all the tests takes place in the first hour of the decay time, whereafter the curve flattens out as the material comes closer to the more stable state (i.e. ground state). The initial steep slope of the graph can be described as transition between the excited state and the luminescing state. This transition is an inherently short time period as expected. This is then followed by the longer transition from the luminescing state to the ground state, which was expected to be a longer time period.

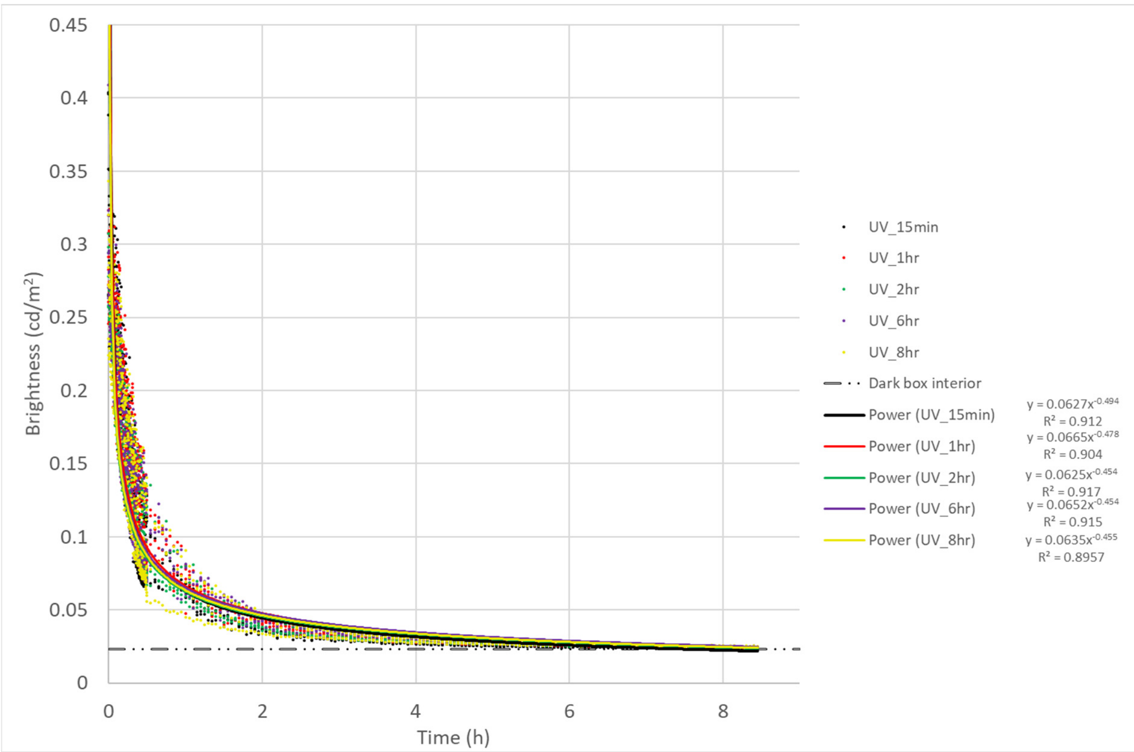

Figure 4-2 Exposure time influence on brightness over time

When considering the first hour of the decay curve, Figure 4-3, the difference between the different exposure times is better visible, also the variability within the repeating of the same exposure times. The decay curve in Figure 4-3 is clear, showing the steep initial gradient and then flattening out. Looking at the different trend lines fitted to the data points (and the individual data points), it can be seen that there is a nearly insignificant difference in the different exposure time tests. There is also no clear indication that a longer exposure time results in a higher brightness. Considering this, it was decided that using a 1-hour exposure time for all further tests in this study would be adequate. Additionally, all the initial brightness's of the different exposure times were fairly similar, with differences being attributed to possible discrepancies in the timing of the light switching off and the camera starting to capture images.

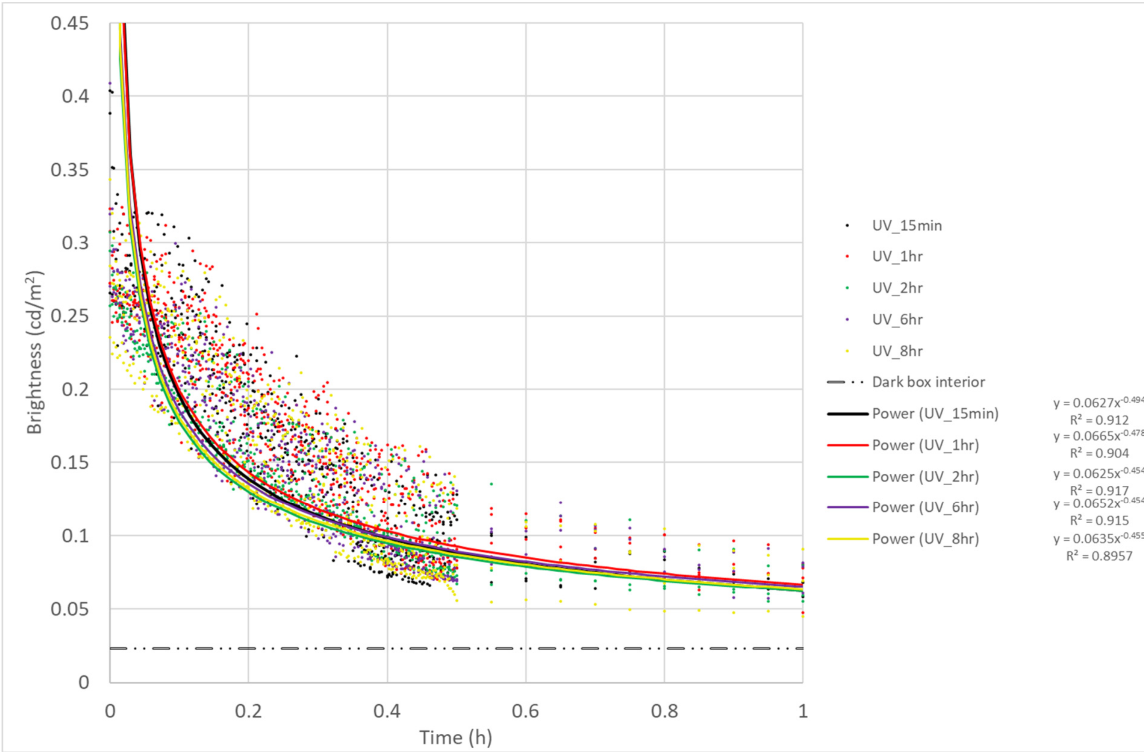

Figure 4-3 Exposure time influence on brightness over time (enlarged)

The results of the different exposure times indicate that there is little difference between the brightness and the decay time of each. This indicates that the exposure time, for the times considered, does not have a significant impact on the brightness of the material and a longer exposure time does not result in a higher brightness or a longer decay time, or the inverse thereof. This may indicate that the aggregate rapidly reaches the excited state with the concentration of the energy available, rather than continuously increasing the excitation state. The level of excitation is therefore determined by the concentration of the excitation energy available rather than the time exposed to the energy source, which is also confirmed in the next section. With that said, it was not tested what an exposure time of less than 15 minutes would deliver, thus the statement is only based on the exposure times considered. However, Wiese et al. (2015) reported to have similar results in terms of the influence of exposure times when exposing a luminescent sealant to a Xenon arc lamp.

4.1.2 Light source influence

The resulting brightness decay curves for each of the considered light sources, discussed in Section 3.3.3, can be seen in Figure 4-4. Although the trendlines of the different light sources are close to one another, a trend can be identified from the results. The results show that as the amount of UV light present in each light source increases, so does the brightness. For this experimental setup, the lowest amount of UV light was with an IR light, increasing to a streetlight, increasing to a fluorescent light, increasing slightly to a UV lamp and finally the sunlight having the highest amount of UV light. This also corresponds to the initial brightness of the material after exposure, where the initial brightness increases as the UV light increases. With the higher amount of UV exposure of the sun, the material also maintains a slightly higher brightness over time compared to the other light sources. When considering the transition between different states, this makes sense as there is more energy which was absorbed, thus a longer time is needed to dissipate the energy and move to a lower state. Even if the higher energy is released at a higher rate, it is believed that the material has an inherent capability of emitting the energy in the form of visible light, and if more energy is available than can be emitted, then a higher brightness can be achieved for a longer time period. Again, it seems that the excitation state of the material is determined by the concentration of the excitation energy, rather than the time of the exposure. However, the material has a limit to the amount of energy it can absorb, thus the excitation state can reach a maximum even if more energy is available. This limit was not tested in this study.

After the first 2.8 hours shown in Figure 4-4, the brightness's slowly converge to a point where the material does not luminesce anymore, which is reached earlier by the streetlight exposure compared to the sunlight.

Considering the results of the 1 hour of sunlight exposure, together with the previous indication that a longer exposure time would not influence the brightness, it can be seen that the decay pattern of the material would entail that the material would no longer be in the excited state or even in the transition to the luminescent state, when night time arrives after sunset. The material would rather be in the luminescent state transitioning to the ground state once the sun has set. In low light conditions this could however be adequate for some applications, such as sidewalks or other environments with low light emitting forms of travel utilising the environment.

Even though the street light showed a low excitation present, it is important to note that an excitation energy was present in the light source. This indicates that if the material is implemented near a street light or other light sources, the possibility exists of exciting the material with existing infrastructure.

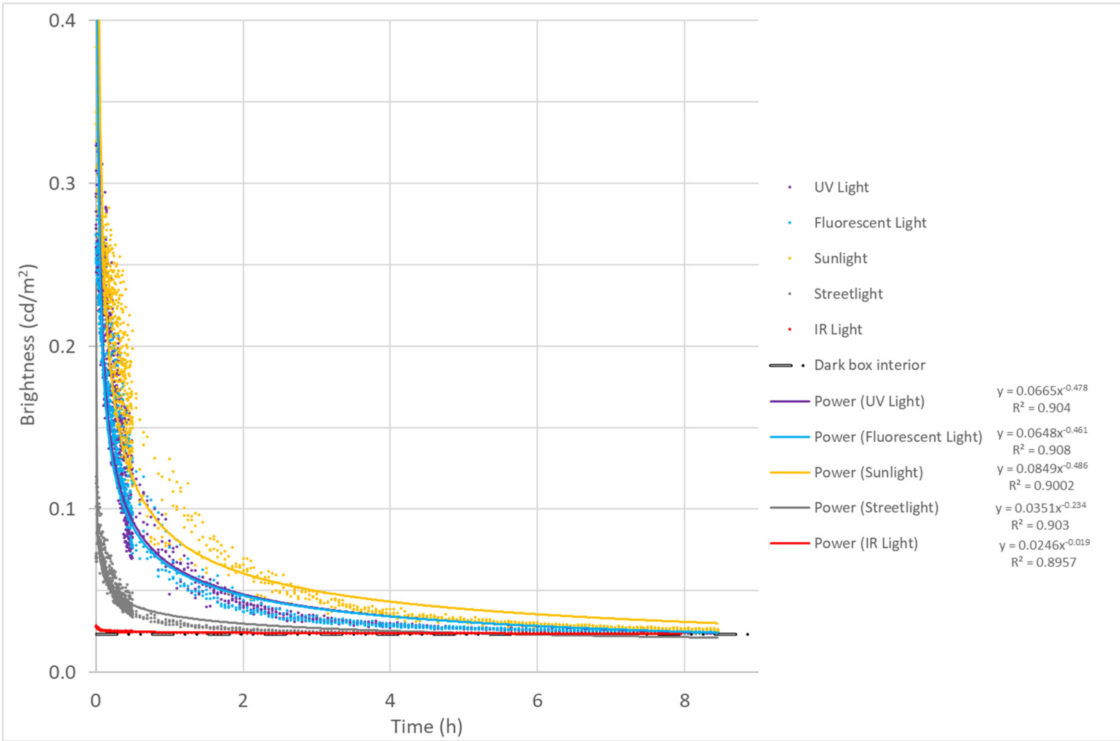

Figure 4-4 Light source influence on the brightness over time

4.1.3 Interval re-exposure

As described in Section 3.3.3, a single aggregate was exposed to a light source at interval times. Figure 4-5 illustrates the resulting plotted data points of the brightness of the aggregate over time, of a single test. The graph starts at a high initial brightness, which is attributed to the initial exposure, whereafter the brightness decays until 15 minutes. At this point a sudden increase in brightness can be seen and the UV light was turned on for 1 minute. The results show that the upward spike in brightness value has a slight curve to the positive side, which indicates that the material does not receive all the excitation energy immediately but rather over time. Once the light source is switched off at 16 minutes, the decay in brightness once again occurs. However, as the collective excitation of this step was less than for the initial exposure, the decay reaches a lower point after a further 14 minutes. Following that, a further two positive spikes occur, indicating the re-exposure to the light source. Another important pattern that can be discerned from Figure 4-5, is that the peaks and valleys of the re-exposed brightness' are similar. This shows that with the correct timing of interval re-exposure of the aggregate, a high brightness can be sustained. From this result, the duration and frequency of re-exposure can be determined to produce a required brightness, or to keep the brightness decay below a certain point.

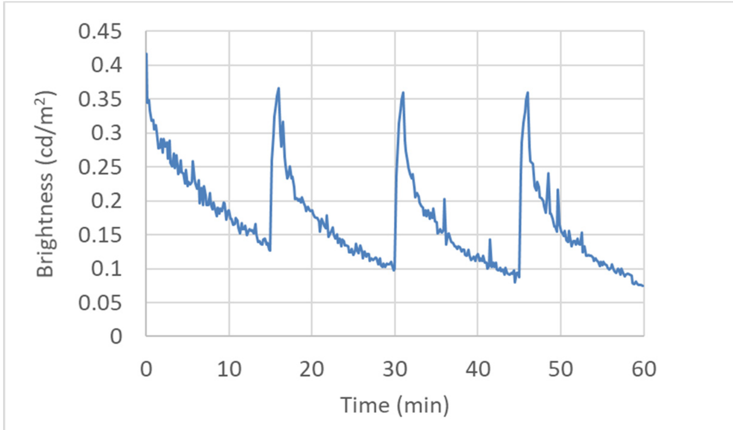

Figure 4-5 Brightness influence of impulse exposure (single test data plotted)

With regards to energy efficiency, this can be used to limit the energy used to excite the material while still achieving a desired brightness. The results also indicate that the material can be re-excited with a short exposure to a light source, even an artificial light source.

4.1.4 Light transmittance through aggregate

To determine, internally, how the luminescent aggregate absorbs and emits light, a single piece of aggregate in a thin slab of concrete was exposed for 1 hour, on side (1) shown in Figure 4-6, whereafter it was flipped over and the brightness was measured on side (2) of the slab. Figure 4-7 shows the resulting images of the aggregate on the side exposed to a light source (left) and on the opposite side of the exposed surface (right). The resulting initial brightness of the exposed surface (1) after the light source was switched off was 0.125 cd/m^2, whereas the unexposed surface (2) had an initial brightness of only 0.025 cd/m^2. Even if the initial brightness of the unexposed surface is low, the results indicate that the material is excited inward, thus the unexposed surface received energy through the aggregate itself to be able to luminesce. This may also be attributed to the luminescing surface on the exposed side possibly being observed through the aggregate, indicating a level of inherent transparency of the aggregate material. This could be observed to a certain extent, when the slab was held up and a bright compact LED light source was moved over the opposite surface of the slab, the aggregate was perceived to light up once the light source passed over the aggregate.

Considering that the material is capable of luminescing on the opposite side of which it is exposed to excitation energy, it can be used to motivate the use of light pathways connected to the aggregate in concrete to conduct light through the concrete unit. For example, aggregate can be imbedded on the surface of a concrete wall to be exposed to an external energy source, with light pathways connecting the non-exposed surface of the aggregate with the interior surface of the wall, supplying light (even if it is a small amount) to the interior space. This can especially be beneficial in interior spaces which do not have access to natural light, such as a basement in a home.

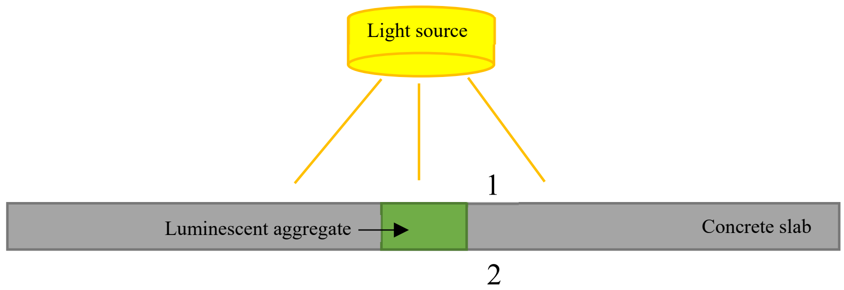

Figure 4-6 Schematic explaining which side of a luminescent aggregate is referred to

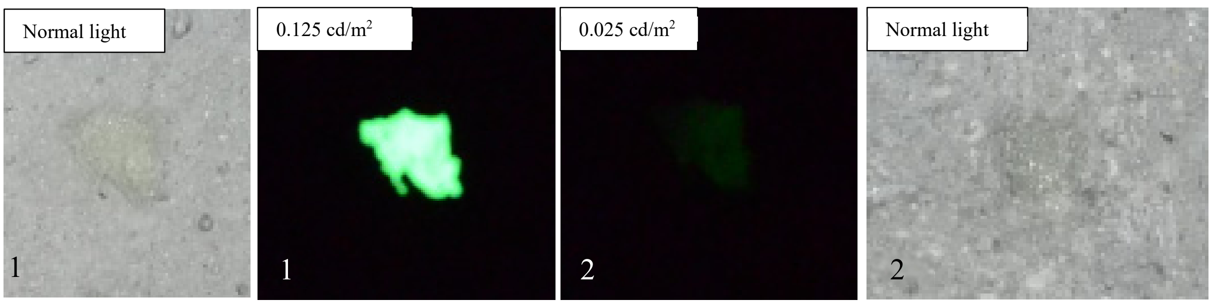

Figure 4-7 Resulting brightness on each surface of the luminescent aggregate

4.1.5 Powder luminescence

The summarised results in Figure 4-8 show the brightness over time of powder luminescent material incorporated into a cement paste cube. The results indicate the rapid initial decay in brightness of the material, whereafter the gradient of the decay curve is reduced until it reaches zero. This can possibly be attributed to the limited amount of luminescent material being exposed to the excitation energy;

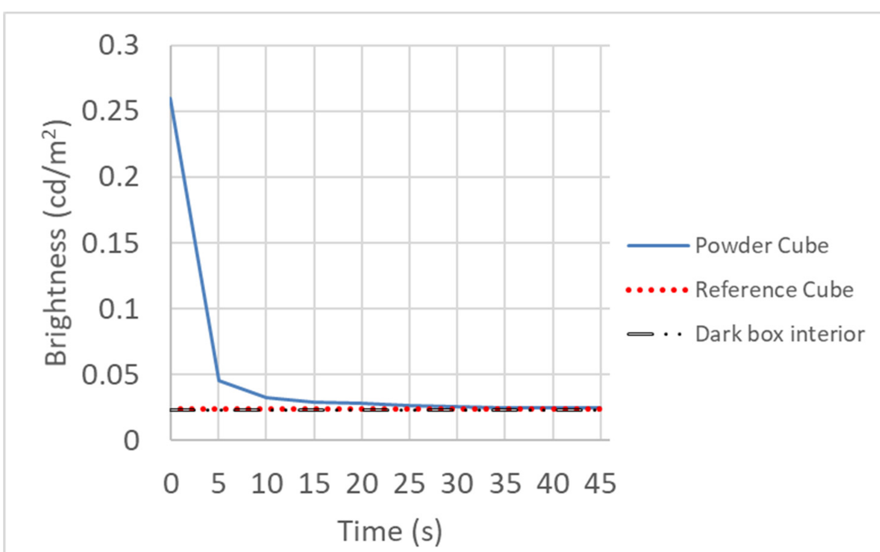

Figure 4-8 Brightness decay of luminescent powder in cement paste (single test data plotted)

thus, the concentration of the luminescent material is lower in the cast luminescent cube than that of the luminescent aggregate previously used. The total luminescent time of the luminescent cube delivered shorter luminescence times that was reported by Zhao et al. (2013), when comparing similar content volumes. They reported more than a factor of 20 times longer luminescence. This could be attributed to a difference in luminescent powder used to create the concrete cube.

Figure 4-9 shows an image of the resulting luminescent concrete utilizing luminescent powder. This is an image of the cube directly after the UV light, which was used to excite the material, was switched off. The light emission may be described as an even glow over the entire exposed surface area. However, as the results indicate, the initial brightness as seen in Figure 4-9 has a very rapid decay, whereafter the exposed surface area has a low brightness and the green colour can no longer be perceived. Four brighter dots also appear in the image, which can be attributed to small lumps of luminescent powder which did not break up during the mixing process, thus the concentration of available luminescent material is higher, therefore resulting in a higher brightness.

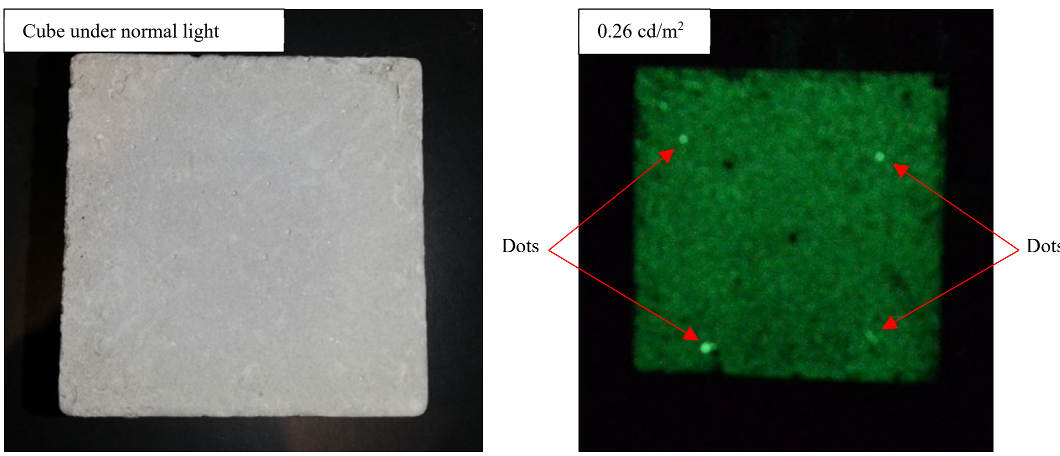

Figure 4-9 Luminescent powder and cement paste cube in different light conditions

By incorporating exposed transparent aggregates to the surface of the concrete unit, the total exposed area of the luminescent material can be increased, as it no longer only has a flat surface exposed, but also the surface at the back of the transparent aggregate. This can possibly improve the luminescent properties of the cube; however, this was not tested. This can be explained by means of Figure 4-10, where the yellow line represents the length exposed to the excitation energy, which can be translated to surface area if depth is added.

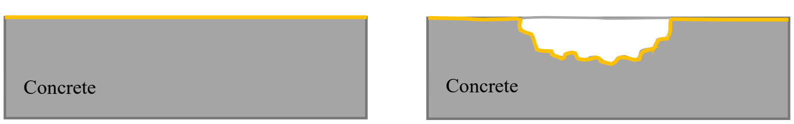

Figure 4-10 Illustration of the increase in exposed area with the implementation of transparent aggregate

4.1.6 Discussion

The results discussed also aided in the characterisation of both luminescent aggregates and luminescent powders. The gained knowledge could be used to produce a light emitting concrete unit, aiding in the main objective of making the concrete more visible in low light conditions.

Considering the results of the exposure times of the luminescent aggregate and the time the light emission remains visible after exposure, it may seem a small window in which the aggregate delivers a perceivable amount of light. Taking into consideration the suggested application of the material, the applicability of the way the material releases light becomes more relevant. For example, referring to Section 2.6.1, it is shown that the time required to evacuate a multi-storey building should be less than 10 minutes (Galbreath, 1969). This shows that the material releases light in such a manner that it would be efficient in providing light for people having to evacuate a building. This would aid in the efficiency of the evacuation of a building if the lights were to go out. Additionally, in most structures fluorescent lights are used as light source during operational hours, which was shown to provide a sufficient amount of excitation energy to the aggregates. For the application of producing a luminescent concrete, different materials are available which can be beneficial in different applications depending on the requirements of the application.

The results of the interval re-exposure can be beneficial in environments where a higher brightness is required of a longer period of time, or even constantly. This can in effect reduce the overall energy used to have sufficiently lit environments.

As for the luminescent powder, the results indicated that the powder emits light over a shorter period compared to the luminescent aggregates, with emission time measured in seconds compared to the aggregate having hours of light emission. This may limit the implementation usefulness of the luminescent powder as used in this study, however if the luminescent powder quantity is altered, the results may be improved.

4.2 Transparency

4.2.1 Fibre optic light transmittance

The results for this experiment show that for the average of three maximum lux values, the blank or empty 0.7 mm hole in the wood measured at 1.4 Lux, and with the fibre inserted the resulting measurement was 5.5 Lux, which is a 300% increase in the light transmittance. Similarly, the 2 mm hole measured a brightness of 17.1 Lux compared to 96.6 lux with the 2 mm fibre inserted into the hole, resulting in a 463% increase in light conduction. The results of the light transmittance of the fibre optic material show that an efficient transmittance is present. Even though the experimental setup used wood instead of concrete to conduct the test, it is still indicative of the light conduction capabilities of the optical fibres, which was the reason for conducting the experiment. The results of the light conduction cannot be compared to previous research, as no previous research was found that conducted a light conduction tests in a similar test setup on a single POF.

Considering how light travels out of the light source, the reason for this occurrence can be explained. As seen in Figure 4-11, only for illustrative purposes, the light travels in straight lines (close to one

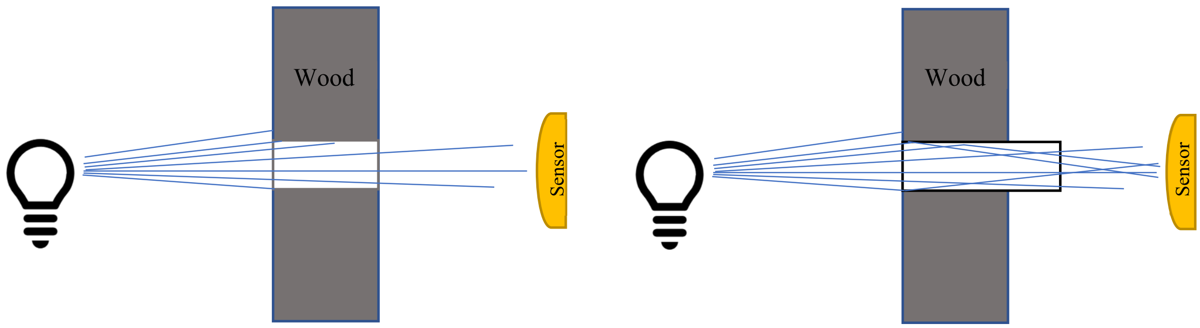

Figure 4-11 Illustration of how light travels through a fibre optic strand placed in a hole

another) from the light source outwards in all directions. These light rays being perpendicular to the surface of the bulb. When the light rays reach the drilled hole in the wood, only the rays travelling straight through the hole, along with a small number of angled rays being reflected off the surface on the inside of the hole, continue on to reach the sensor. With the amount of light that can pass through reducing as the size of the hole reduces. When the fibre optics are placed in the holes this effect changes. As discussed in Section 2.2.1 of the literature review, the fibre optic material has an entry angle of 60° (Zhou et al., 2009). This means that the light rays that were previously lost to absorption by the wood on the side of the hole, can now be transmitted through the material as the light is reflected from the inner wall of the fibre optic. The illustration shows how more light rays reach the sensor with the fibre placed in the hole.

A further advantage of using fibres, instead of holes in material, to transmit light is that the fibre optic material would be able to transmit light in non-straight line, whereas holes are limited to near straight lines. The placing of the fibres can be made easier as they are not limited to straight lines, and additional lighting effects can be achieved by the arrangement of the fibre optics.

4.2.2 Resin light transmission

The result of the brightness recorded for the light travelling through the 5 mm hole in the wood was 165,3 lux. The ultra-clear casting resin was placed in the hole, and the resulting brightness was recorded as 52.4 lux, whereas the normal casting resin had a similar maximum brightness of 52.0 lux. By using Equation 3-4 the percentage of light lost by travelling through the resin was calculated. The ultra-clear casting resin resulted in a 68.3% loss in light, and the normal resin resulting in a 68.5% loss. This is lower than the light transmittance of the fibre optic material and can be attributed to the inherent transparency of the material used in each. The results obtained show a poorer performing material than the recorded 8% loss of light by Mainini et al. (2012). The difference can be attributed to the difference in test setup and construction methods implemented in creating the resin prisms.

However, even if this is a high loss in the amount of light travelling through the medium, the use of a resin instead of a hole in the concrete would be beneficial for the durability of the concrete, and could reduce the loss in strength of the concrete as a result of a void in the concrete matrix. This is because the resin has a higher compressive and tensile strength compared to an air void. Figure 4-12 shows the light being transmitted by a protruding resin prism before being inserted into the hole. This shows how the light travels through the resin, with a large amount of light being emitted from the side surface of the prism. With a suggested addition of reflective material on the side surface of the prism, the light may be more effectively transmitted to the end of the prism. This was however not tested. The light seen emitted out the side of the prism is lost to the inner walls of the hole drilled in the wood when the prism was inserted for testing, similarly to what was described in Section 4.2.1.

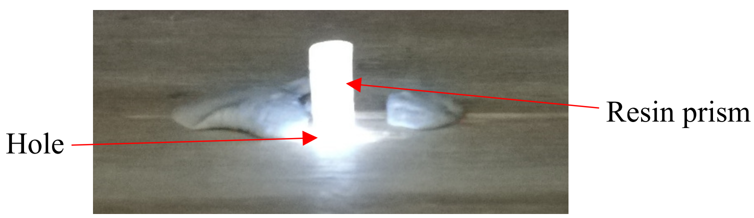

Figure 4-12 Light travelling through resin prism, with light emission through sides

A luminescent aggregate was placed on the emitting side of the resin prism to test if UV light can be transmitted through resin material, and for both the resins considered, the luminescent aggregate received excitation energy. This can be utilised by placing the luminescent aggregate inside the concrete matrix, with excitation energy being transmitted to the aggregate through the resin from an external light source.

The exposed surfaces of the resin prisms can also be polished to a smoother finish to further improve the light conducting capabilities. An advantage of using resin as a light conducting material in concrete rather than fibre optic material, would be the reduction in the labour intensity of the production of light pathways. Resin can be cast into voids created in the concrete matrix (by a designed mould), whereas individual fibre optic strands should be placed by hand.

4.2.3 Glass light transmittance

Two methods of producing the test samples, for the light transmittance through glass aggregate concrete, were tested. As discussed in Section 3.3.5, the first unit tested was compressed glass, injected with a cement paste. The unit delivered an unimpressive result, with little to no light passing through, which was surprising as the thickness of the unit was only 2 to 3 layers of glass surrounded by cement paste, as shown in Figure 4-13. It was however noted that light was emitted towards the side of the unit, if a light source was placed close to the edge of the unit. This can be an indication that the unit is indeed capable of transmitting light, however limited to a single layer of glass aggregate. A second sample prepared in the same fashion confirmed that light only travels through the first layer of glass, or in other words, only through the glass aggregate directly exposed to the light source and the other unexposed end of the unit. With the low amount of light traveling through the unit, an almost 100% reduction in brightness was measured. The lux value of 0.13 lux travelling through the unit compared to the 892-lux measured over the open 28 mm hole.

Figure 4-14 Three-layer glass unit

A similar result was achieved with the second method of construction, where the lux value only reached a maximum of 0.07 lux with the unit in place. Considering that the glass unit only contained glass in the centre of the cube, with a layer of glass held in place by cement paste surrounding the glass core, the light seems to be restricted by the cement paste between the glass layers. The light reaching the surface of the unit in effect still only travelled through one layer of glass held in place by cement paste. Figure 4-14 illustrates the resulting light emission through the unit, while being placed over the hole drilled in the wood. The light seen emitted at the base of the unit, which is light passing by the unit, was blocked out for the purpose of recording the brightness of light transmitted through the unit.

Figure 4-13 Glass unit under normal light conditions and when placed over hole above stable light source

The results of these two construction methods indicate that it is possible to use glass to produce light pathways in a concrete matrix, but to do so efficiently the thickness of the concrete should be limited, or is determined, by the thickness of the glass aggregate used. This corresponds with the findings of Rouvas (2013).

4.2.4 Discussion

By comparing the three different transparent materials tested, the results indicate that for the purpose of creating light pathways in concrete POF performed the best with the highest light conduction. However, when comparing the different materials which can be used to create light pathways in concrete, other factors which were not discussed in this study such as constructability, complexity of light pathways and cost should also be taken into account.

4.3 Safety

4.3.1 Visual comparison of distances

By using camera settings and methodology discussed in Section 3.3.4, which allowed the environment to be captured similarly to that perceived by the human eye in the specific environment, images were recorded of a luminescent road sign at different distance intervals. The resulting images captured from a distance of 5 m, 20 m, 50 m, 80 m and 100 m are shown in Figure 4-15. The sign is clear from a distance, of about 120 m, directly after the charge was received from the light source, however as the brightness starts to decay, the visible distance is reduced. The results illustrate how implemented luminescent aggregates would be perceived in low light conditions, at different distances.

As expected, from a further distance, the luminescent sign is less noticeable compared to a close distance. The images presented are small, thus the sign is seen as only a dot on the figure for the 100 m distance. However, it is important that the sign is still noticeable, even with the image being small. This indicates that the luminescent aggregate has successfully made an object, which would otherwise be unnoticed, noticeable from a distance in low light conditions. This can be an indication of the possibility that the luminescent aggregates possess to make hazardous concrete structures, or other structures, more visible in low light conditions. The implication of this would be that a hazardous structure or object could be noticed from a safer distance in low light conditions, compared to the same structure not incorporating the luminescent aggregates.

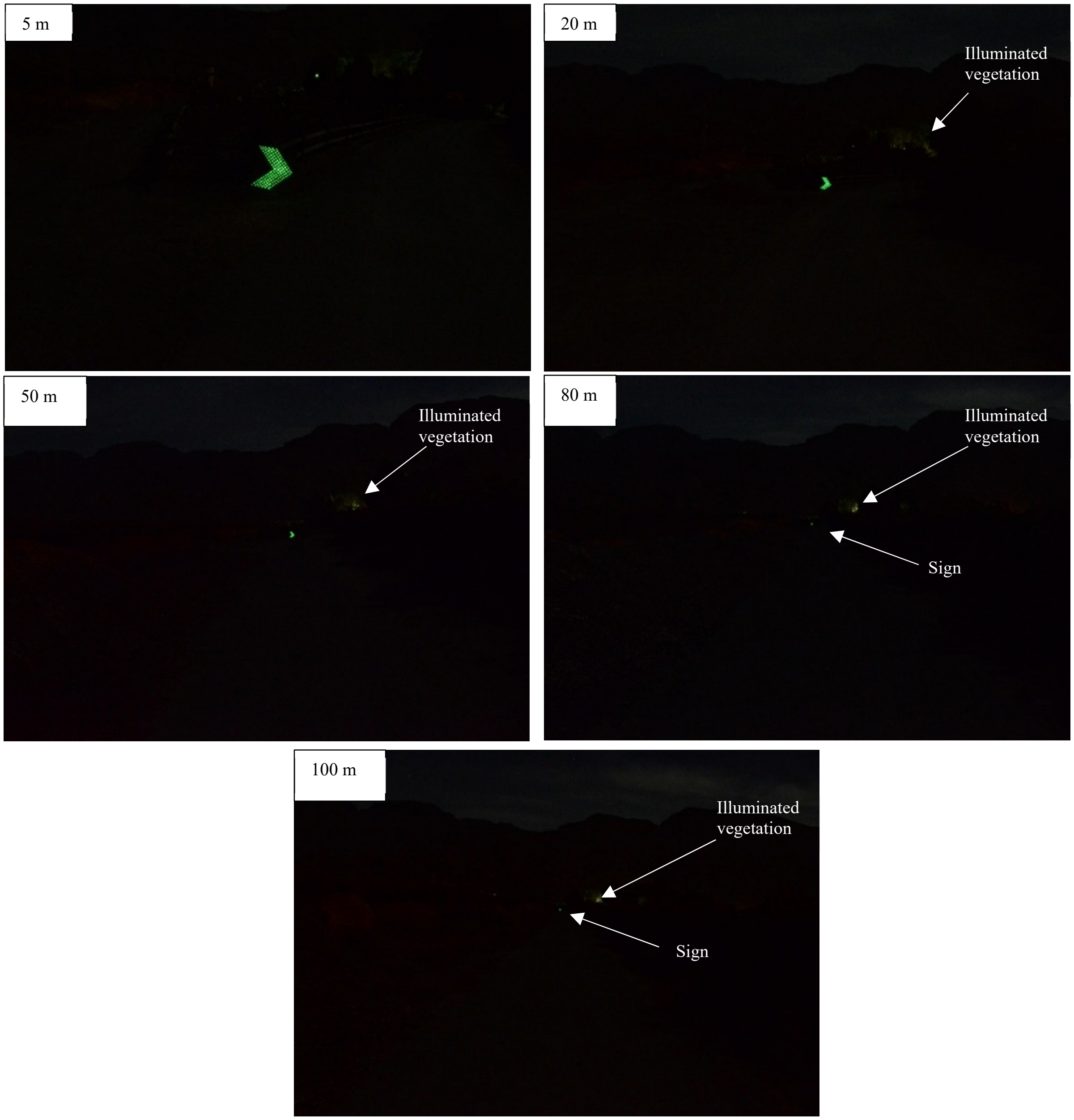

Figure 4-15 Distance visibility comparative images of luminescent sign

4.3.2 Human perception of road sign

As described in Section 3.3.4 an experiment was conducted where the distance from which participants can identify a luminescent road sign (i.e. a known object) after exposure to a light source for 30 seconds. The results were observed at distances of 80 m, 88 m, 104 m and 125 m, after which the sign was charged again, resulting in that the participants stated that the shape of the luminescent sign was clearer from the previous mentioned distances, as the sign was again in the excited state. The participants stated that the luminescent sign draws attention to it when looking around in the area. These results correlate with the visual comparison results discussed in the previous section.

Comparing these distances with that of the prescribed 45 m (South African Government Gazettes, 2008) which vehicles head lights (low beams) may illuminate, it can be argued that the visible distance of the road sign is such that it would be beneficial to road users, especially if the luminescent aggregate is used on a surface that is not illuminated by any artificial light. This indicates that the implementation of the luminescent aggregates can be beneficial to illuminate hazards along the path of travelling. Even if the person perceiving the object which is illuminated, cannot clearly identify what the object is, the user has at least noticed that there is an object in or close to the path of travelling, giving more time to react to the object compared to only noticing an object once the headlights of the car illuminates it. This can be especially relevant when a user is travelling around a bend in the road, and an object can be noticed in the peripherals before the headlights, which mostly illuminates in a straight line ahead of a vehicle, can illuminate the object.

4.3.3 Road edge illumination

Section 3.3.4 described the setup for this field test. The visual representation shown has been captured on the same stretch of road used for the field test of the observable object. Figure 4-16 shows the resulting images of the environment under the three mentioned conditions. The images illustrate that the road is barely visible in low light conditions, even more so the turn in the road which is clearly visible in the daytime. The camera captured the image as presented with the camera immediately detecting light, however the aggregates became more visible for two bystanders, after sufficient time more so than seen on the images, as the human eye adjusted to the environment, after looking at the bright camera display. It was however noted that the luminescence was not visible while driving on the road with a vehicle having bright headlights overpowering the low brightness of the luminescent aggregates. This may suggest that either the concentration of the aggregates should be increased, or that the implementation should be focused on transport without bright artificial lights, such as pedestrian footpaths.

Even if the luminescent aggregates may not be visible directly in front of the vehicle, it may still present capacity to serve as guidance for road users in areas not being illuminated by any source of artificial light. This can be for instance when approaching a multidirectional crossing. Figure 4-17 illustrates a vehicle (grey block) at a four way stop, with the yellow lines representing the area that is illuminated by the headlights of the vehicle. If the vehicle was to turn left or right, the edges of the road, which fall outside of the illuminated area, may not be clearly visible if no streetlights are present. Adding the luminescent aggregates to the edge of the road surface, or to the curb stones, the light provided may aid the driver in determining where the edge of the road is.

Figure 4-16 Visual comparison of road edge illumination

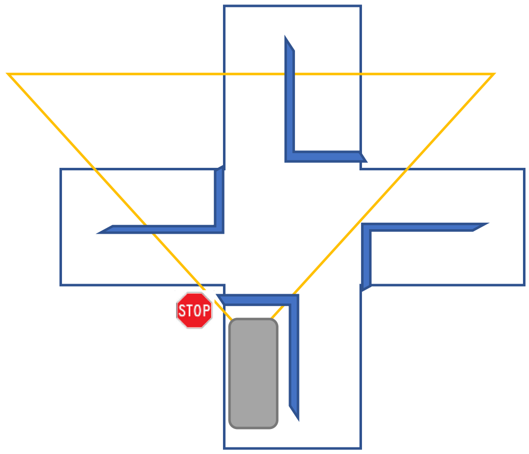

Figure 4-17 Four way stop illustration

4.3.4 Discussion

Even though the light provided by the luminescent road signs may seem to be a small amount, the addition could be helpful to increase road users' ability to notice warning signs or hazards from a safe distance. The implementation of a luminescent road sign on road side concrete structures will assist in illuminating the hazards along the road. The results discussed in this section could not be compared to previous studies as no previous studies was found which conducted similar tests on luminescent materials.

Providing guidance for a user on the road surface, in this form, may be more effective for slower moving modes of transport or for modes of transport which do not have bright lights used to illuminate the surrounding areas, such as pedestrians or cyclists in rural areas. When considering that the human eye can adjust to environmental conditions over time to be more efficient at detecting light, it can be regarded as a valid statement that the luminescent material would be more beneficial to users who travel in a constant low light environment. As the time increases where the user is in a constant low light environment, the human eye would become more sensitive to light sources with a low light emission which was initially missed, and the user would find the guidance from the light emitted by the luminescent aggregates useful. Users without artificial light sources to illuminate the environment would find it easier to notice the light emitted from the luminescent aggregates than users with artificial light.

4.4 Durability

As the additions, which are suggested to be implemented, are mostly implemented on the surface or come in contact with the surface of a concrete unit, it is important to determine what the influence would be on the durability of the concrete once each is implemented. To determine this, the OPI was determined for each of the luminescent aggregate, the 2 mm optical fibre, and the 0.7 mm optical fibre. Figure 4-18 illustrates the resulting OPI of each. In comparison to a reference concrete, all resulted in a decrease in the durability of the concrete unit. The addition of the luminescent aggregate showed a reduction in average OPI of 1.26%, the 2 mm fibre showed a reduction of 2.34% and finally the 0.7 mm fibre showed a reduction of 1.57%, all compared to the reference average OPI. No previous research was found that can support or contradict the results obtained by this test method and materials considered.

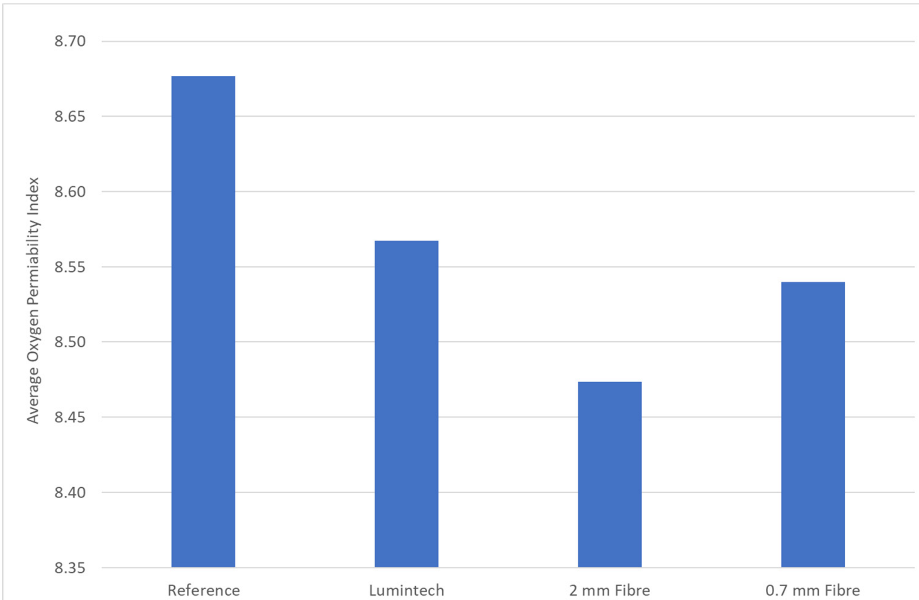

Figure 4-18 Average results of OPI tests

When considering the reduction in durability as a result of the addition of luminescent aggregate to the surface of the concrete, it can possibly be attributed to a difference in the bond between the surface of the luminescent aggregates with the rest of the concrete matrix in comparison to the natural aggregates. Alternatively, the method of incorporation of the material into the matrix could result in a change in durability. The calculated coefficient of permeability for the luminescent added concrete unit was 2.71 nm/s, which is 0.602 nm/s faster than the reference concrete.

When considering both the fibre additions to the concrete, it was expected that the durability would decrease, as the fibre directly connects both top and bottom surfaces. As the fibre is made of an extruded plastic (PMMA) it can be assumed that the oxygen did not pass through the fibre, but rather through the surrounding concrete matrix. The calculated coefficient of permeability for the 2 mm fibre added concrete unit was 3.37 nm/s, which is 1.26 nm/s faster than the reference concrete. The calculated coefficient of permeability for the 0.7 mm fibre added concrete unit was 2.93 nm/s, which is 0.816 nm/s faster than the reference concrete. A possible explanation for the reduction in durability could be that at the interface zone between the fibre and the paste, a higher water-cement ratio may be present, together with more air voids, which allows easy movement of oxygen. Again, the method of incorporating the material into the matrix could be the cause of the reduction in durability. It is important to notice that the reduction in durability is present, but is lower than expected. Furthermore, it was expected that the larger cross-section fibre would be less durable compared to a smaller equivalent. This is as a result of a larger circumference around the exposed end of the fibre, and a larger surface area around the fibre passing through the concrete unit. It is again important to note that this is only a single fibre added to a concrete unit, increasing the volume of fibre material in a concrete unit may further reduce the durability thereof. A limitation should be noted with this test, being that these results represent the addition of a fibre to a concrete mix, and would not necessarily represent the outcome of fibre placed in a cement or mortar mix.

With implementing the suggested concepts, which resulted in reducing the durability of the concrete unit, the possibility of implementing a surface sealant to improve the durability can be considered. However, the level of reductions in the durability are not too concerning, thus slightly changing the original concrete mix should be sufficient to compensate for the reduction.

4.5 Combined concepts

Using the material advantages of both the luminescent aggregate and the POF, a concrete unit was produced to highlight the advantage of each material and how they can be used in conjunction with each other. Using Figure 4-19 and Figure 4-20, some of the possible placements of the material in a concrete unit are illustrated. Figure 4-19 shows a luminescent aggregate placed on the surface of the unit which is exposed to a source of excitation (yellow arrows), and a fibre optic strand is connecting the opposite (unexposed) surface to the luminescing aggregate. If the material is set up in such a fashion, the luminescent aggregate would be excited by the source, and emit light (green arrows) through the fibre to the other surface. Once the source is removed, the light would continue to be emitted through the fibre, but also from the aggregate on the surface.

Alternatively, the placement of the material can be changed to match Figure 4-20. In this illustration, the excitation energy would be transmitted to the imbedded luminescent aggregate through a POF. The light then emitted by the luminescent aggregate can then be transmitted to other surfaces again using POF.

A combination of both of these placement methods were implemented to create the combination concrete unit.

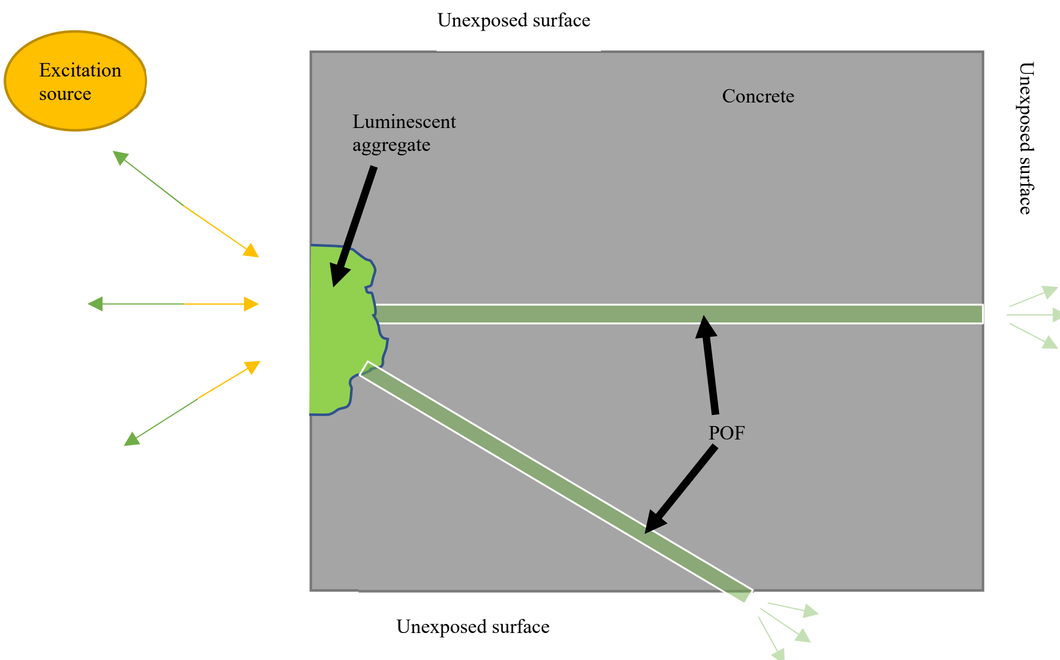

Figure 4-20 Combination unit material placement A

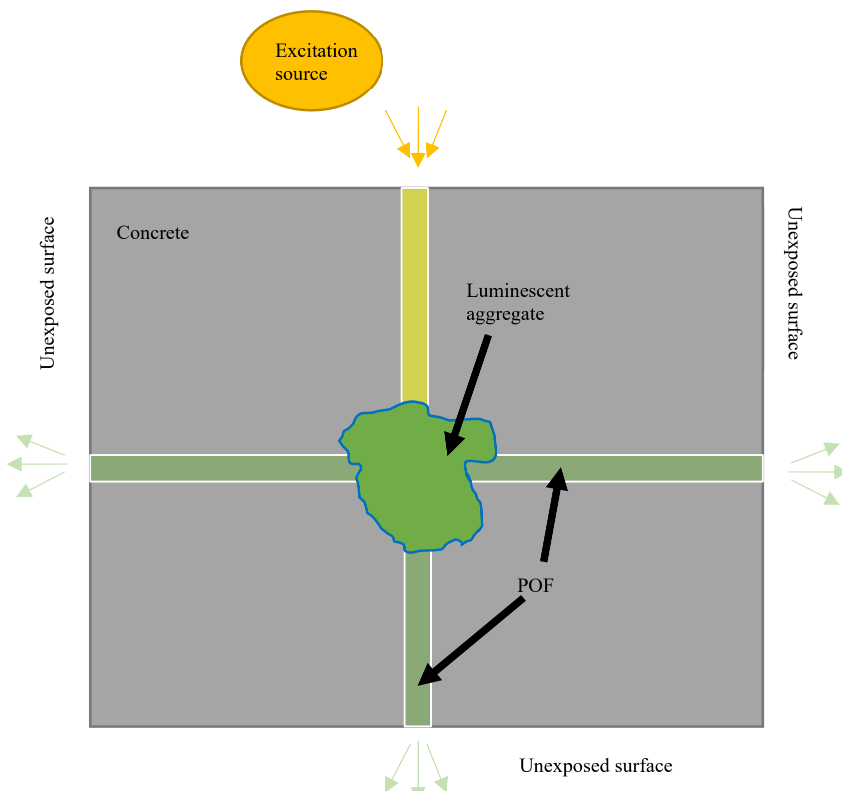

Figure 4-19 Combination unit material placement B

The following section only describes the implementation of selected concepts to produce a final concrete unit. As described in Section 3.3.8, the light emission is incorporated by luminescent powder, luminescent aggregate, and transparency incorporated by 2 mm fibre optic material and resin prisms. Figure 4-21 illustrates a normal concrete unit (bottom) and a top view of a concept incorporated unit (top) under fluorescent light, with both units polished until smooth and first aggregates were visible. Figure 4-22 illustrates the concept unit side profile, revealing the fibre and resin material. Both figures can be used to show that in normal light conditions, both look very similar.

Figure 4-23 illustrates the fibre optic on the opposite surface of a surface exposed to a LED light source. This shows how the light is able to be transmitted to the other surface of the concrete unit, thus not blocking the available light for illumination. The larger light dots seen in Figure 4-24 are the two resin prisms placed in the concrete to serve as a light pathway, showing again the similar brightness achieved by the different resin materials. Figure 4-25 in turn illustrates the luminescent material emitting light, after being exposed to a light source, in a low light condition next to a reference concrete unit not being visible. The concept unit illustrates that with the light emitting luminescent material implemented, the visibility of the concrete unit in low light conditions is enhanced.

Additionally, the randomly spaced fibres seen in the centre of the figure are transmitting light which is travelling through luminescent aggregates exposed to the light source on the opposite surface. This illustrates that light can be transmitted through the luminescent aggregates while a light source is available, and when the light source is removed the material can continue to provide light. Some of the fibres are, as seen in Figure 3-21 in Section 3.3.8, connected to a luminescent aggregate placed in the centre of the unit with fibres connecting the outer surfaces to the aggregate (LuminFibre), similar to Figure 4-20. The fibres connected to luminescent aggregates can be seen luminescing through the fibres in Figure 4-26, with light sources removed. This is an important illustration of the potential of the combination of luminescent and translucent materials. The illustration proves that the luminescent material can be implemented in a centralised position where it can receive optimal exposure to excitation energy, whereafter the light being emitted after the light source is removed can be rerouted to another location in the concrete matrix where light is needed. Finally, in Figure 4-27 the combination of the different concepts can be seen, together with the fibre optic material conducting light around a 90° turn in the beam, with the LED light source being placed on the bottom side of the beam and the light being emitted at the front surface.

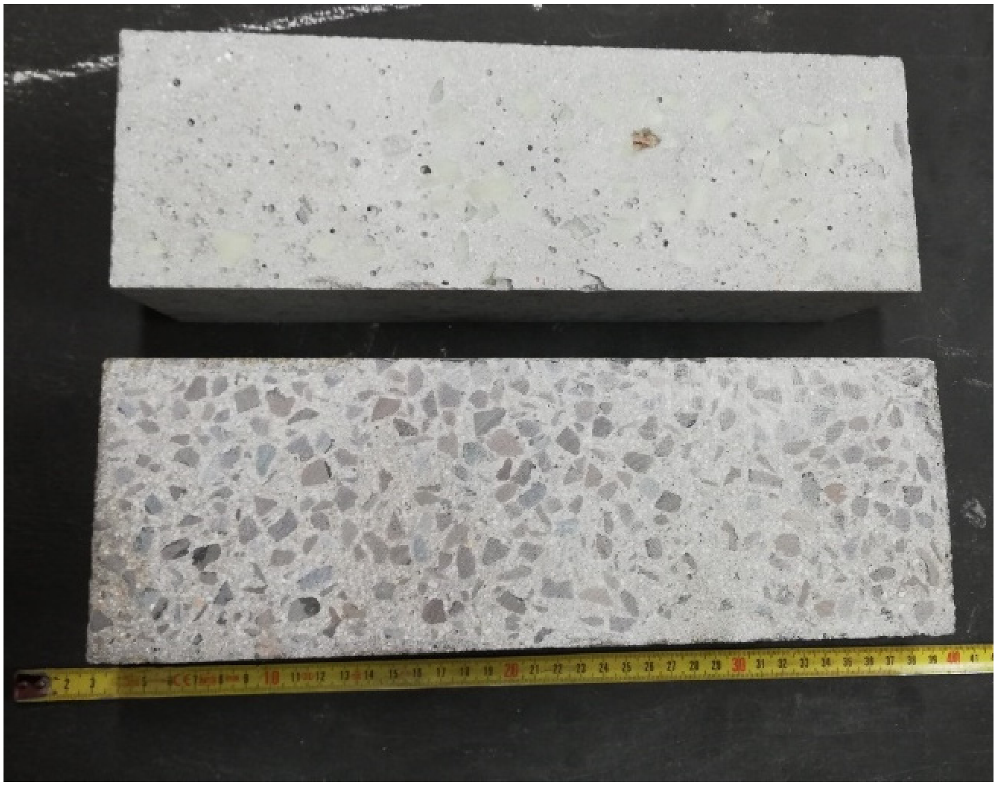

Figure 4-21 Unit comparison: Top – polished surface with luminescent material, Bottom – polished surface of reference concrete unit

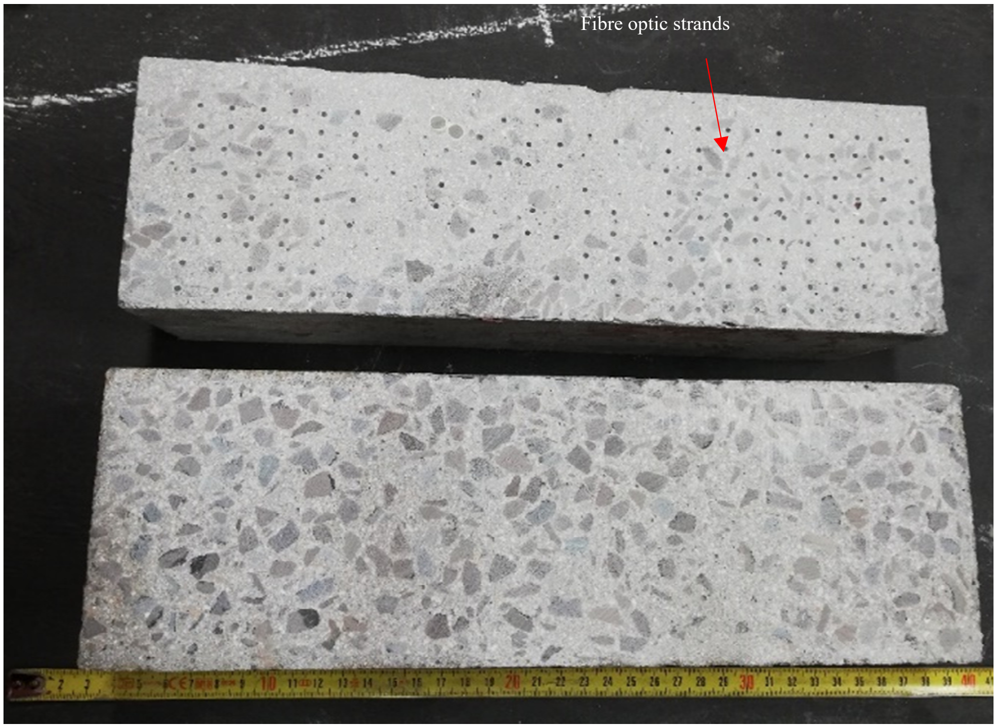

Figure 4-22 Unit comparison: Top – polished surface with fibre optic material, Bottom – polished surface of reference concrete unit

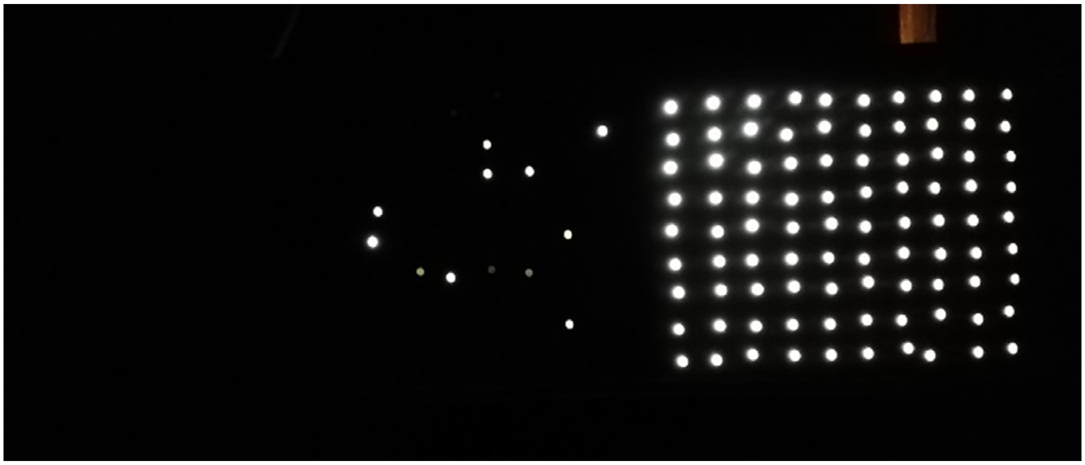

Figure 4-23 Light passing through the fibre optic strands from one surface of the concrete unit to the other

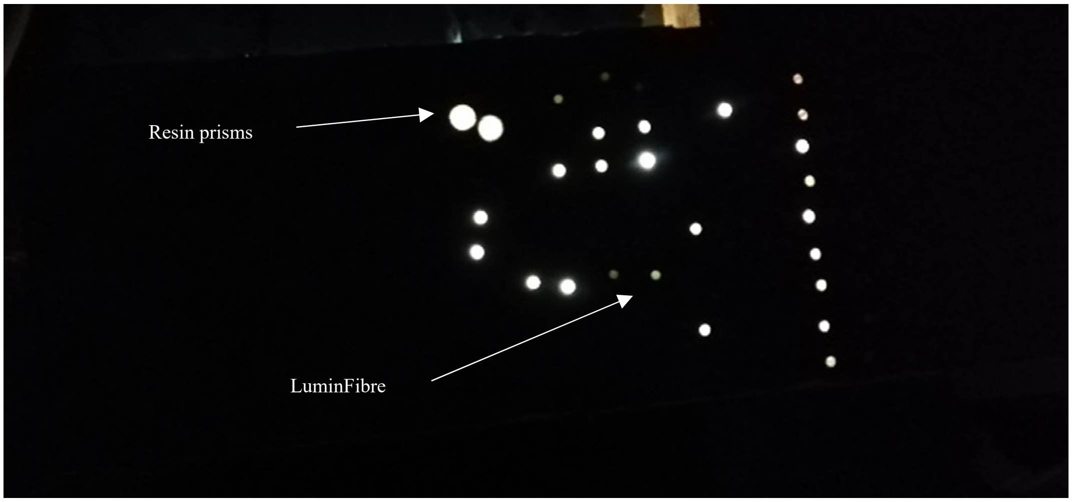

Figure 4-24 Light passing through resin prisms and luminescent fibre optic (LuminFibre) combination

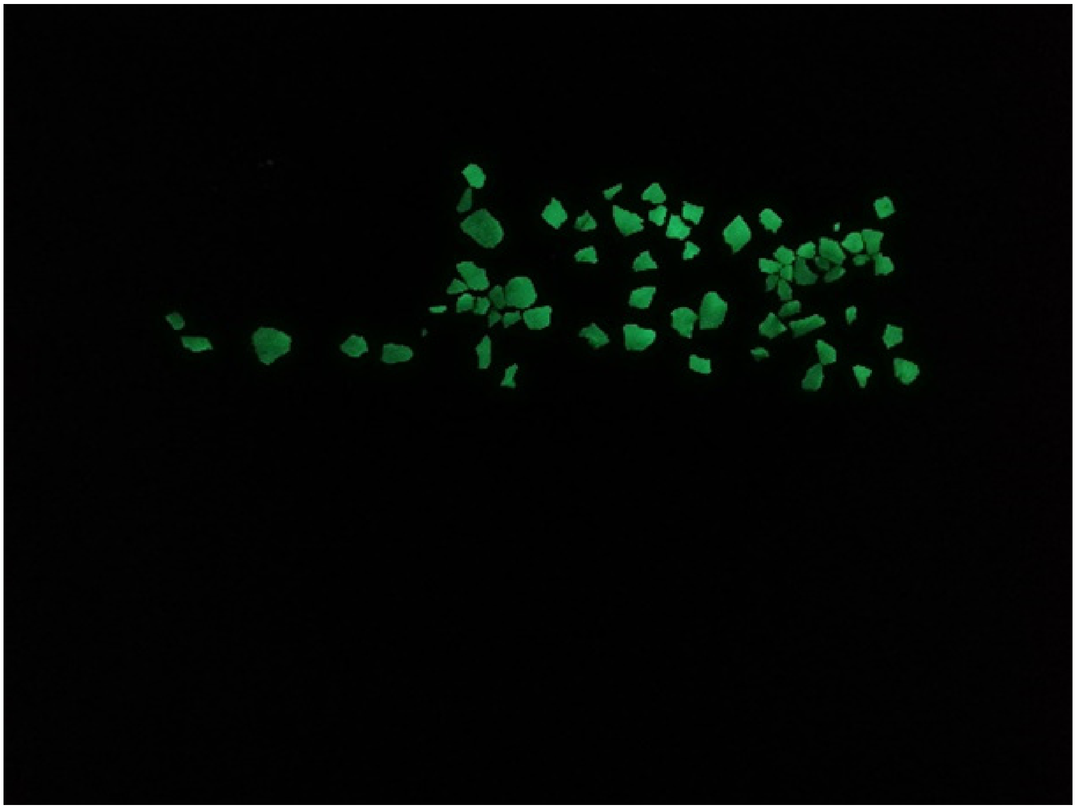

Figure 4-25 Unit comparison: Top – Luminescent material making the unit visible in low light conditions, Bottom – polished surface of reference concrete unit

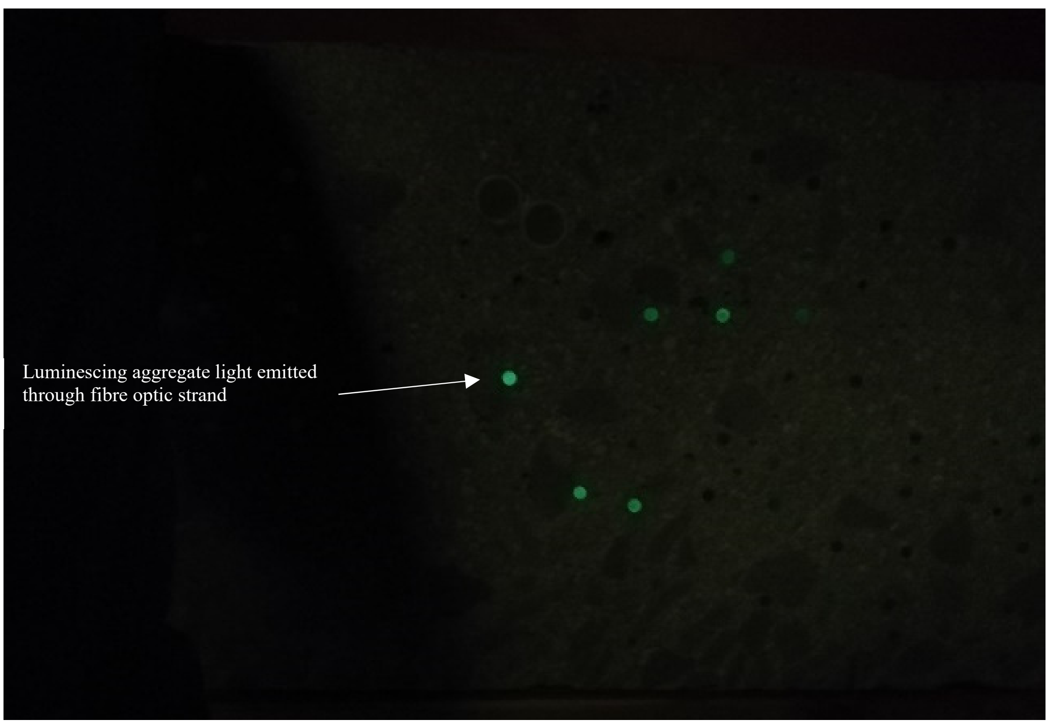

Figure 4-26 Light emitted from luminescent material through fibre optic strands

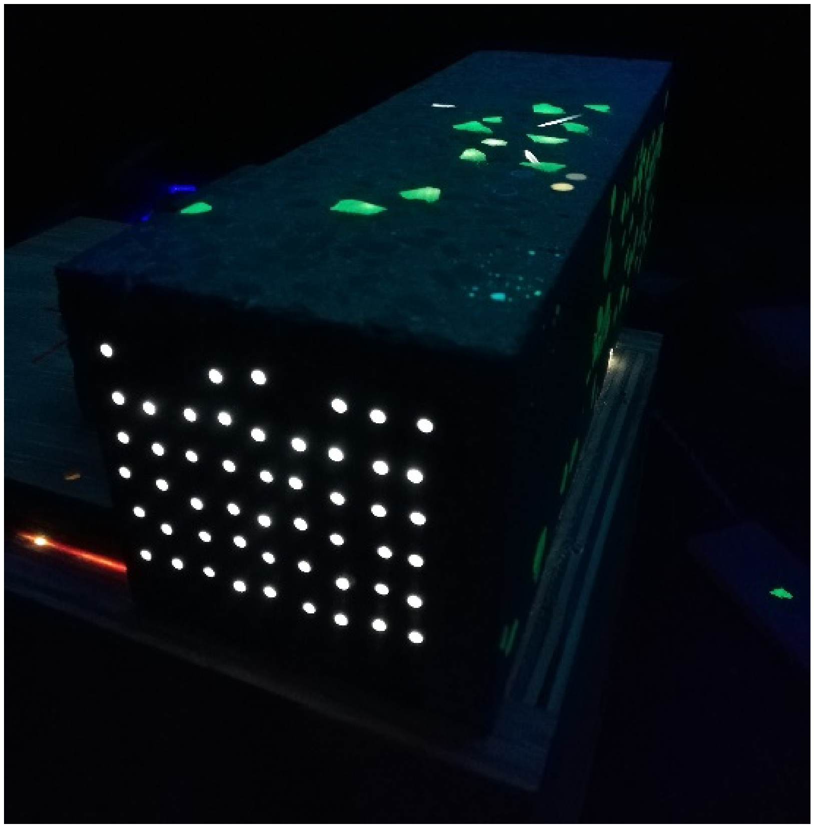

Figure 4-27 Illustration of the combined concepts in one unit

The placement of the different materials in the combination unit was chosen to incorporate the different placements to illustrate the versatility of the materials once they are combined. For example, the placement of the POF to direct light around a 90° turn shows that the light pathways created by the use of POF is not limited to straight lines. Thus, if a POF is connected to an excited luminescent aggregate, the POF can transmit the emitted light to any other surface in the concrete unit.

4.6 Aesthetics

The survey that was discussed in Section 3.3.7, and attached as Appendix B, was completed by a total of 45 individuals. The recorded responses were processed and the majority of participants, 82.2% and 86.7% respectively, preferred the aesthetic appearance of the reference polished concrete over that of the polished luminescent aggregate and fibre optic surfaces, under fluorescent light conditions. The choice of a normal polished surface over that of the luminescent aggregate surface can possibly be attributed to the contrasting effect which was achieved by the Greywacke stone against the lighter grey paste surrounding the stone, which is clearly visible under the fluorescent light. The opposite was present for the polished luminescent aggregate, under the fluorescent light the pale luminescent aggregate blended in with the surrounding grey paste.

When the same polished luminescent aggregate was compared to the polished reference concrete surface under only UV light, i.e. the luminescent aggregate was luminescing, the preferred surface changed to the polished luminescent surface with a vote of 86.7%. The change of opinion by the individuals can possibly again be attributed to the contrast created between the luminescent aggregate and the surrounding paste under an excitation source which does not overpower the brightness of the luminescent aggregate, or the addition of colour to the unit (Toogood, 2014).

An average likelihood of implementing the combination concept as an aesthetic surface finish instead of normal concrete, which is either polished or painted, was 7.69 on a scale of 1 to 10, with 1 being less likely and 10 being more likely. The combination concept was presented to the participants under a UV light to illuminate the luminescent aggregate, while a stable LED light source was transmitted through the fibre optic material, see Figure 4-25. The high likelihood of the implementation thereof can possibly be attributed to the fact that most humans prefer something new over something old (Wittmann et al., 2008), and for the participants the concepts illustrated are novel.

Even though the results of the survey are not quantitative but rather qualitative, it can still be seen as a good indicator of the aesthetics of the concrete with the incorporated concepts.

5 Conclusions and recommendations

The objective of this study was to develop a concrete concept which incorporated existing concepts to attempt to improve the visibility of concrete, especially in low light conditions. Considering the investigation into the different aspects discussed in this study, the following main conclusions could be drawn:

- When considering the influence of different exposure times on the brightness over time, it can be concluded that (for the exposure times considered) the time of exposure does not positively or negatively influence the initial brightness of the luminescent material or the decay over time. Thus, short exposure times of around 15 minutes are adequate to excite the luminescent material.
- Considering the influence of different light sources on the brightness over time, it was found that as the amount of UV light in the light source increased, so did the brightness of the luminescence. Thus, using a light source with a high amount of UV light (with different wave frequencies) would be beneficial to produce a higher luminescent brightness.
- The brightness of the material can be "replenished" with short interval exposure, of around 60 seconds, to a light source.
- Considering the use of fibre optic material as a light transmitting medium, it was found that using fibre optics instead of just a hole to transmit light is 463% more effective when compared at a size of 2 mm. Furthermore, the fibre optic material can be used to conduct light around bends, which would be beneficial for constructability.
- Implementing transparent or translucent materials into the concrete matrix allows for a centralised light source to emit light from different points through a concrete unit, depending on the placement of the materials.
- The combination of transparent and luminescent materials is possible, and it can be beneficial to improve visibility in low light conditions to incorporate the two in conjunction with each other.
- The use of resin to produce light pathways into and through concrete is possible.
- Adding the luminescent material to road signs can be seen as an expensive addition, however it can be deemed useful in illuminating concrete hazards on road sides. Since it is able to help in identifying objects under low light conditions.

- A recognizable object can be seen from a safe distance when illuminated by the luminescent aggregate, and observers state that it shifts focus towards the illuminated such that one would notice the object in low light conditions.
- The luminescent aggregate can effectively be incorporated into concrete to aid in providing guidance for pedestrians which are slower moving and without a light source.
- The inclusion of both luminescent and transparent materials can reduce the durability of the concrete in which it is placed, with the level of reduction related to the volume of included materials.
- The aesthetics of concrete can be improved by the implementation of the various concepts.

Taking these points into account and by implementing the investigated alterations to a concrete unit, the improvement of the visibility of concrete in low light conditions can be achieved by using the concepts, materials and methods used in this study.

Recommendations for those who wish to further investigate the concepts discussed in this study, and to possibly further improve on the concepts discussed, are as follow:

- The use of a combination of different luminescent materials is recommended to improve the overall light emission of the concrete unit.
- Develop relevant construction methods to efficiently incorporate both luminescent and transparent material.
- The use of luminescent concrete would be more beneficial to transportation modes which have a low light presence in an environment, above a mode having high illuminating light sources.
- If fibre optic material is to be used in concrete to produce light pathways in large quantities, it is recommended that a cheaper alternative be considered to the high quality POF used in this study.
- Consider the implementation of side emitting fibres in combination with luminescent powder.
- Add reflective material around resin prisms to improve light transmittance.
- Consider the implementations of reflective material to add to the visibility of concrete in low light conditions.
- Consider producing own luminescent aggregate such that better control and variation in luminescence of a concrete unit can be possible.

- Conduct a cost analysis, comparing the combination of different transparent materials and luminescent materials.
- Incorporate the luminescent material as an overlayer on an existing road sign to benefit from the reflective nature of the road sign at a close distance.

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Appendix A

MATLAB R2018b code implemented to conduct image processing for brightness experiments (Section 3.3.1).

```
clc

clear all
format short e
F = 5.6
t = 1/5
S = 6400
focal_length = 105
max_aperture = 5
Kc = 4.15625
%prompt = 'What is the experiment number? ';
%x = input(prompt);
prompt = {'Test name:','Experiment number: ','Folder name:','Photo number start:','Photo
number finish:'};
dlgtitle = 'Experiment Details';
dims = [1 35];
definput = {'TestHanru','30','Folder','Start','End'};
opts.Interpreter = 'tex';
answer = inputdlg(prompt,dlgtitle,dims,definput);
test_number = str2num(answer{2});
test_name = answer{1};
folder_name = answer{3};
first = str2num(answer{4});
last = str2num(answer{5});
sstring = sprintf('%04d',first);
estring = sprintf('%04d',last);
start = str2num(sstring);
finish = str2num(estring);
results = [];
dateTime = [];
i = 1;
row = 3;
time = 0;
k = start;
areapixel = [];

BaseName1 = 'F:\Hanru\';                                           %H
filename1 = [BaseName1,folder_name,'/','HMN_',sstring,'.NEF'];
image_variable=imread(filename1);
d1 = imfinfo(filename1);
ty1 = d1.FileModDate;
tstart = datetime(ty1, 'InputFormat', 'dd-MMM-yyyy HH:mm:ss')

for k=start:finish
%k = 2324
y = 56;
x = 75;
photonum = sprintf('%04d',k);
BaseName = 'F:\Hanru\';
filename = [BaseName,folder_name,'/','HMN_',photonum,'.NEF'];
```

```
image_variable=imread(filename);
row = 1;
%imshow HMM_2324.NEF
gray_image=rgb2gray(image_variable);
    for y=48:80                                %this should choose what
                                                %pixels to use
       %x = 74;
        for x=54:87
            pixel_valueA=gray_image(y,x);                %(60,80)
            NdA=pixel_valueA;
            areapixel(i,row) = pixel_valueA;
            row = row+1;
        end
    end
% %pixel_values = impixel
% pixel_value1=gray_image(60,80);                  %(60,80)
% Nd1=pixel_value1;
% %sprintf('The value of the pixel is %d', pixel_value);
% pixel_value2=gray_image(61,77);                  %(64,80)
% Nd2=pixel_value2;
% pixel_value3=gray_image(59,79);                  %(60,77)
% Nd3=pixel_value3;
% pixel_value4=gray_image(62,80);                  %(57,78)
% Nd4=pixel_value4;
% pixel_value5=gray_image(60,82);                  %(60,82)
% Nd5=pixel_value5;
d = imfinfo(filename);
ty = d.FileModDate;
asns = datetime(ty, 'InputFormat', 'dd-MMM-yyyy HH:mm:ss');
%s = char(asns);
areapixel(i,1) = k;
areapixel(i,2) = seconds(asns - tstart);
%dateTime(i) = s;
i = i+1;
time = time+10;
end
% imshow HMM_2324.NEF
% pixel_values = impixel
% sprintf('The value of the pixel is %d', pixel_value);
% originalImage = imread(filename);
% [rows, columns, numberOfColorChannels] = size(originalImage);
% gray_image=rgb2gray(image_variable)
areapixel
% T=array2table(results,...
%     'VariableNames',{'PhotoNumber', 'Time', 'PixelValue1',
% 'Luminence1', 'PixelValue2', 'Luminence2', 'PixelValue3',
%'Luminence3', 'PixelValue4', 'Luminence4', 'PixelValue5', 'Luminence5'} )
BaseName = 'F:\Hanru\';
p = array2table(areapixel);
filename = [BaseName,folder_name,'/',test_name,num2str(test_number),'.xlsx'];
% filename = 'C:\Users\USER\Desktop\Universiteit\M\Research\Photos/Data1.xlsx'
writetable(p,filename,'Sheet',1,'Range','A1')
```

Appendix B

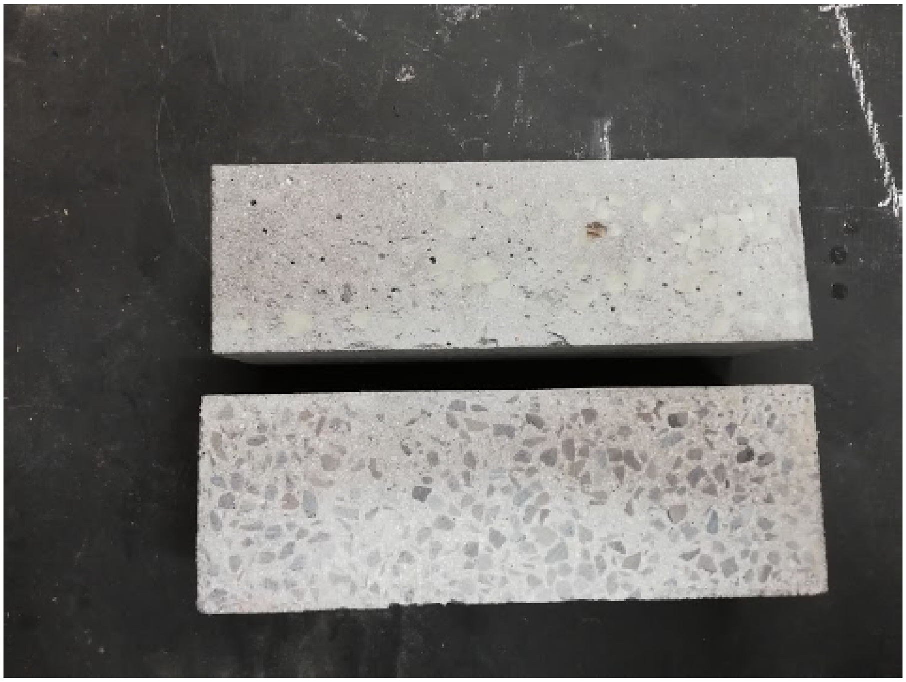
A blank survey, used by participants to provide their opinion on the aesthetic value of a concrete unit. (Discussed in Section 3.3.7 and Section 4.6)

Aesthetics of Concrete - By Hanru Muller

An investigation was launched to determine the possibilities of improving the visibility of concrete in low light conditions. As a result of the implementation of different concrete concepts, the resulting concrete concept appeared to have improved aesthetic value from that of a normal concrete matrix.
This survey was created to determine, if with certain additions to a concrete matrix, the aesthetics of a concrete unit, or of concrete as a building material, can be improved. As there is no quantitative method to measure aesthetics, the results of this survey would serve as a qualitative measurement for the investigation.

For each of the following images, please select the relevant option according to your perception there of?

1. For the following image, which of the two units (top or bottom) would you say has the better aesthetic value?

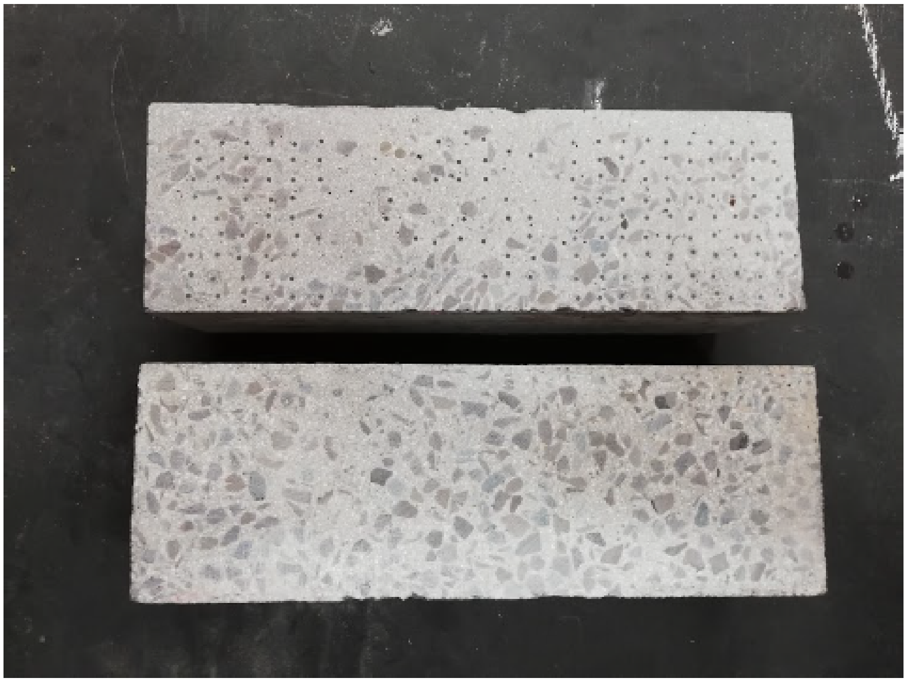


Mark only one oval.

- Top unit
- Bottom unit
- Either, they look similar

D

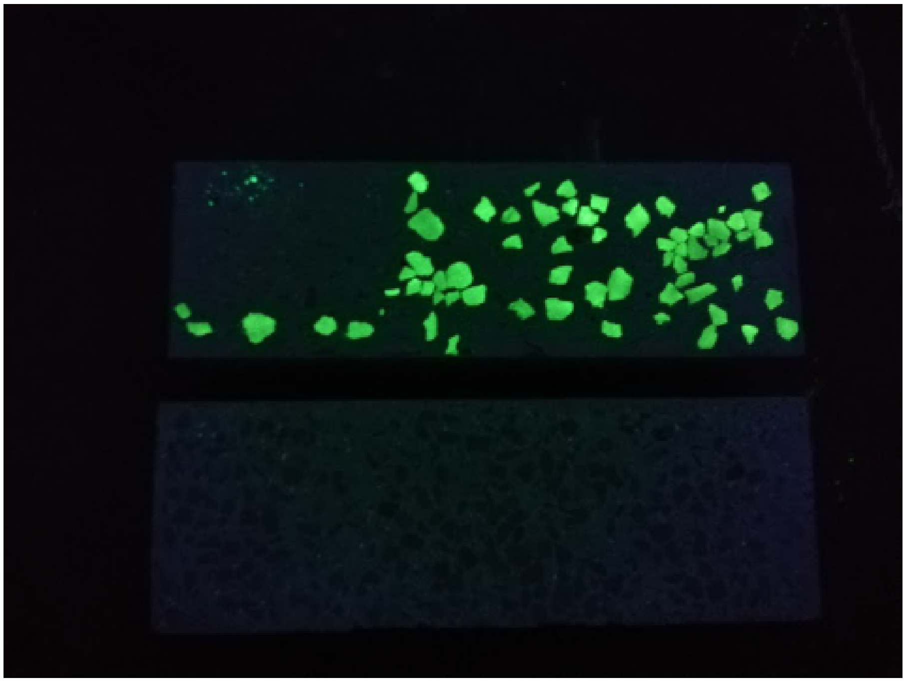
2. For the following image, which of the two units (top or bottom) would you say has the better aesthetic value?



Mark only one oval.

- ( ) Top unit
- ( ) Bottom unit
- ( ) Either, they look similar

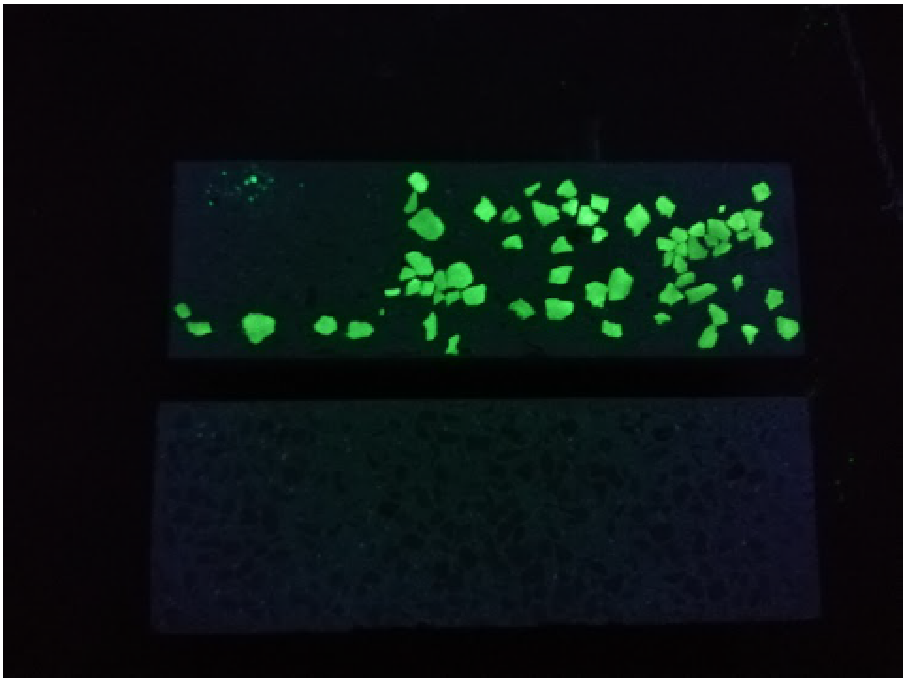
3. For the following image, which of the two units (top or bottom) would you say has the better aesthetic value?



Mark only one oval.

- ( ) Top unit
- ( ) Bottom unit
- ( ) Either, they look similar

4. For the following image, which of the two units (top or bottom) would you say has the better visibility in the light conditions on the image?

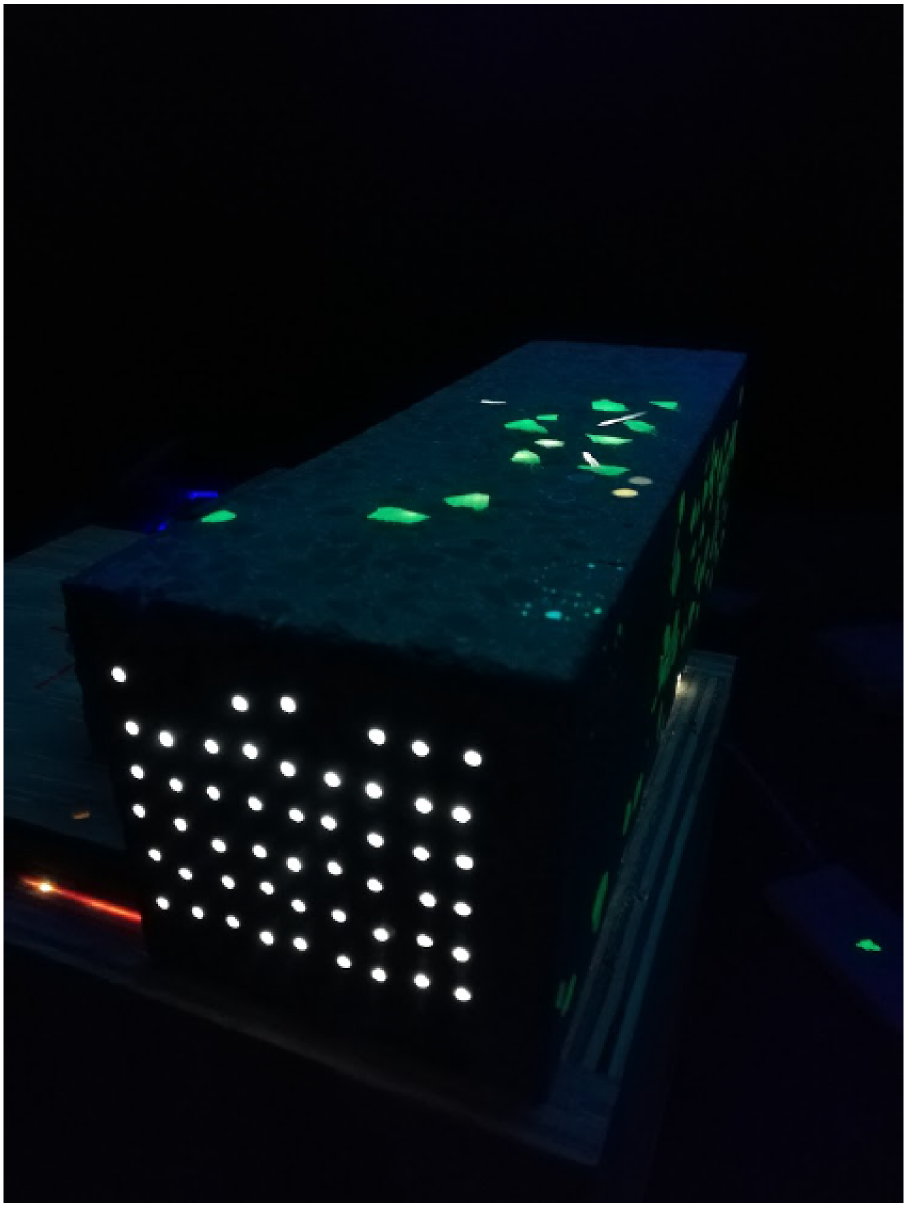


Mark only one oval.

- Top unit
- Bottom unit
- Either, they look similar

G

5. On a scale of 1 to 10, with 1 being less likely and 10 being more likely, how likely is it that you would consider choosing the following concrete as a construction material for aesthetic finish of a structure you are building instead of normal concrete, which is then either polished or painted over?



Mark only one oval.

1 2 3 4 5 6 7 8 9 10

Less likely ◯ ◯ ◯ ◯ ◯ ◯ ◯ ◯ ◯ ◯ More likely